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VARIATIONS IN PRECIPITATION AS AFFECTING WATER WORKS ENGINEERING

By Carl Peter Birkinbine

INTRODUCTION

The source of all water supplies, whether surface or underground, is the precipitation of aqueous vapor from the atmosphere; commonly as rain, but also in the frozen forms of snow, sleet and hail. These last are eventually reduced to water and, while their depths are often measured, the recorded quantities are expressed as equivalent water. Part of this precipitation is again evaporated into the atmosphere, other falls directly on the water surface of lakes, swamps or streams, some is transpired by vegetation, a portion runs off directly from the ground surface; the balance entering the soil. Surface waters and streams and the subsoil supply feed the water courses and basins above and below the surface and at various distances from the point of deposition.

All these actions take place in irregular intervals varying in duration, and may be much extended, except that direct or surface runoff is generally limited to brief periods; and the proportions of each vary with the topography, geology, geographical location, character and physical conditions of watershed and its cover, season and climate, which last embraces barometric pressure, temperature, humidity and wind, and with the conditions before, during and after the precipitation.

Water works engineering for domestic supply covers a field of utilization recognized by the courts as the most important application of water supplies and as a primary claim on them. The original source, from wherever taken, is the precipitation, and as this varies there are created different conditions to be met, requiring individual studies.

It is the purpose of this paper to discuss some of these irregularities and extremes, and the requisite provision by which water works engineering meets the conditions, the treatment being general with some instances. It is to be remembered that all examples are specific cases, and while typical of certain "rainfall regions," are to be considered from that view point. Records at some locations may not appear requisite illustrations for studies because of local conditions of development or utilization, but these typify certain rainfall divisions whose precipitations benefit water resources.

Though there is a demand for more climatological data, those available offer such a multitude of interesting examples that any general discussion must limit the number quoted to a few. It is also necessary to omit any detailed exposition of relation between rainfall and runoff, so as not to extend the discussion beyond proper limits.

In compiling data reference was made to our office records, technical literature, published reports and to the various government publications, especially those of the United States Weather Bureau, which has collected by far the greater part of such information. The author expresses appreciation of the courtesies extended by Prof. Charles F. Marvin, Chief of the Weather Bureau, his assistants in charge of the various departments, and by the gentlemen in charge of the various Weather Bureau Stations, and acknowledges the willing assistance of Mr. George S. Bliss, Section Director, and Mr. M. B. Summers, First Assistant, of the Philadelphia office, and Prof. Oliver L. Fassig, in charge of the Baltimore office. Thanks are also offered to his brothers and to associates in the office, for assistance in the compilation of data and review of the manuscript; and acknowledgment of data is also made to the Water Supply Commission of Pennsylvania.

The national scope of this Association suggested that this paper include some of the different precipitations in the United States, which, by virtue of the great area, length of coast, distances between oceans, and the varying topography, experiences a very large range in the quantity and distribution of moisture deposited. Alaska,

the insular possessions, and the Isthmus of Panama, are omitted, although their precipitations are interesting.

Precipitation in Continental United States includes: average annual totals, ranging from approximately 125 inches to 3 inches; individual yearly records varying from 162.5 inches (Glenora, Oregon, 1899) to 0.10 inches (Mohawk, Arizona, 1895);[1] deposition in a single month as high as 41.63 inches (Upper Mattole, California, January, 1888); an individual daily record of 21.4 inches (Alexandria, Louisiana, June 15–16, 1886); even a quantity of 11.5 inches in 1¼ hours (Campo, California, August 12, 1891).

As of interest are mentioned Cherrapunje, India, which annually receives about 600 inches, mostly in 4 to 6 months, with a record of 905 inches in the year 1861; and Baguio, Philippine Islands, with a 24-hour precipitation (July 14–15, 1911) of 46 inches, measured by an automatic recording gauge.

Water works engineering is herein used in a comprehensive sense to include, not only studies for enlargements or new developments, but also maintenance and operation. To the vagaries of precipitation are ultimately related the requirements of domestic and industrial supply, fire protection and sanitary improvement, the potability of the water, its composition and requisite treatment, the physical features of a system, the methods of obtaining and delivering water, and provisions for disposing of it after use.

PRECIPITATION

Precipitation is a feature of Climatology, but for present purposes the actual occurrence of the deposition of moisture is sufficient.

While it is recognized that much moisture is evaporated from land surfaces and their cover, the rate from exposed water is much higher, and the major portion of this vapor is withdrawn from the oceans, which cover three-fifths of the earth. The Continental United States has, with the included portion of the Great Lakes, only 4 per cent of its area water surface, but is contiguous to two oceans, the Gulf and the Great Lakes. Moisture-bearing winds from the oceans contribute mainly to the precipitation over the States, in amounts varying with topography, distance and meteorological conditions.

[1] Bagdad, California, received no measurable rainfall in the year 1913.

Evaporation, the antithesis of precipitation, is also its major cause, and obviously the two must balance for the earth as a whole, but their local variation is universal.

Plate 1 typifies on a general scale the topographic conditions of our country, and plate 2 indicates the average occurrence of depositions.

Winds, of different classes, play an important part in the condensation of moisture. The city of San Francisco is surrounded by water except on the south, and in summer, when winds from land to sea largely predominate, the average, of 63 years' records, shows that less than 1 per cent of the total precipitation occurred in June, July and August; while if May and September are added, the proportion for the 5 months was but 5½ per cent.

The Middle Atlantic Coast Region, which receives storms from the Lakes, the Gulf and Atlantic coasts and the southeast, as well as thunderstorms, shows a relatively small variation in seasonal averages. Cyclonic circulation is a prime cause of precipitation and the chief agency in its distribution in temperate latitudes.

Other variations take place by reason of storm paths. The ocean storms frequently gain in velocity when crossing the land and condense at varying rates as specific conditions occur.

The greater rainfall of warmer latitudes is well illustrated along the Atlantic Coast and Gulf Region, while Southern California demonstrates how wind direction produces deficiency of rainfall in a humid district. (See plates 2 and 32.)

The manner in which elevations in topography create condensation of moisture carried in ocean breezes is illustrated by the higher rainfalls which most of the Alleghenies receive as compared with regions on either side, and by the heavy precipitations which occur on the Cascade and Sierra Nevada ranges; also by the variations in inland states. (See plate 2.)

To the water works engineer the most important features of precipitation are its deficiencies and excesses. Long term records are of great service, and will give mean values that represent average conditions for a lengthened interval, and are also valuable as being more likely to indicate ranges in extremes, which are important in considering supply.

Investigation of precipitation records suggests that any records established by actual occurrence may at any time be set aside, but it must be remembered that extreme conditions are of uncommon


RELIEF MAP OF THE UNITED STATES.
Birkinbine. Variation in Precipitation. Plate.-1

NORMAL ANNUAL PRECIPITATION IN THE UNITED STATES, 1870-1901.

and irregular occurrence, and that the past two decades have witnessed an enormous increase in precipitation records. The variability of precipitation occurs through periods ranging from extended to brief duration, and in all records the *relative* variation is to be noted. That is, the proportionate amount of any departure from the normal may be more weighty than the actual quantity.

An early recognition of the importance of variations in stream discharge, which is the result of precipitation, is noted in Egyptian history when Amenemhat III, about 2300 B.C., instructed that the height of the Nile be noted on the rocks at the fortress of Semnet, 2nd Cataract, and these engravures are still visible. Other ancient Nilometers are at Memphis and near Cairo, this last having a record of operation of over 1100 years.

Unfortunately there are but few continuous protracted records which show the eccentricities in adjacent periods of various durations.

Extended records may also be totalled into periods of several or a number of years, and plates 34 to 38 illustrate, for specific localities, how the variation in average is reduced as the interval is lengthened. In such averages proper consideration must be given to the effect of extremes, for years of excessive or subnormal quantities in sequence, or in close proximity, will have different effects according to their occurrence in an interval.

Considerable attention has been given by investigators to the reliability proportion of records of various lengths, and the individual annals, the mass curves, and the smoothed curves of averages show that it is important to consider the quantity characteristics of the periods which records cover.

ANNUAL PRECIPITATION

It is recognized that the use of a year in records is not always satisfactory, and a more uniform "water year" is obtained by beginning the 12 months with some date other than January 1, or by dividing the year into hydrologic sections. The data thus obtained are often more suitable for study, though subjected to the varying quantity and distribution of the different portions of the year.

As a unit of comparison the annual precipitation is frequently used, and plate 4 illustrates for specific localities the inconstancies of this quantity, especially to be considered where large storage to cover long periods is required.

Table 1 lists some extremes of the annual precipitation and Table 2 notes the effect of the inconstancies on averages for the year and month.

TABLE 1

Some extremes of annual precipitation and their proportion

LOCATION	INTERVAL	INCHES OF ANNUAL PRECIPITATION			PER CENT OF MAXIMUM TO MINIMUM
		Average	Maximum	Minimum	
Boise, Idaho	1868–1914	13.81	25.80	6.69	386
Boston, Mass	1818–1914	44.10	67.72	27.20	250
Des Moines, Iowa	1879–1914	32.23	56.81	18.24	311
Detroit, Mich	1871–1914	32.00	47.69	21.06	226
Grand Junction, Colo	1893–1914	8.24	11.61	3.64	320
Little Rock, Ark	1880–1914	49.11	75.54	33.32	230
Los Angeles, Cal	1877–1914	15.71	38.18	5.59	683
Madison, Wis	1869–1914	31.71	52.91	13.49	392
New Orleans, La	1836–1914	56.05	85.73	31.07	276
Omaha, Neb	1871–1914	29.68	48.92	15.49	316
Pueblo, Colo	1889–1914	11.78	18.58	6.14	302
Richmond, Va	1872–1914	41.63	72.02	27.65	260
Rochester, N. Y	1871–1914	33.69	49.89	20.30	245
St. Louis, Mo	1837–1914	39.96	68.83	23.38	294
St. Paul, Minn	1837–1914	27.31	49.69	10.21	486

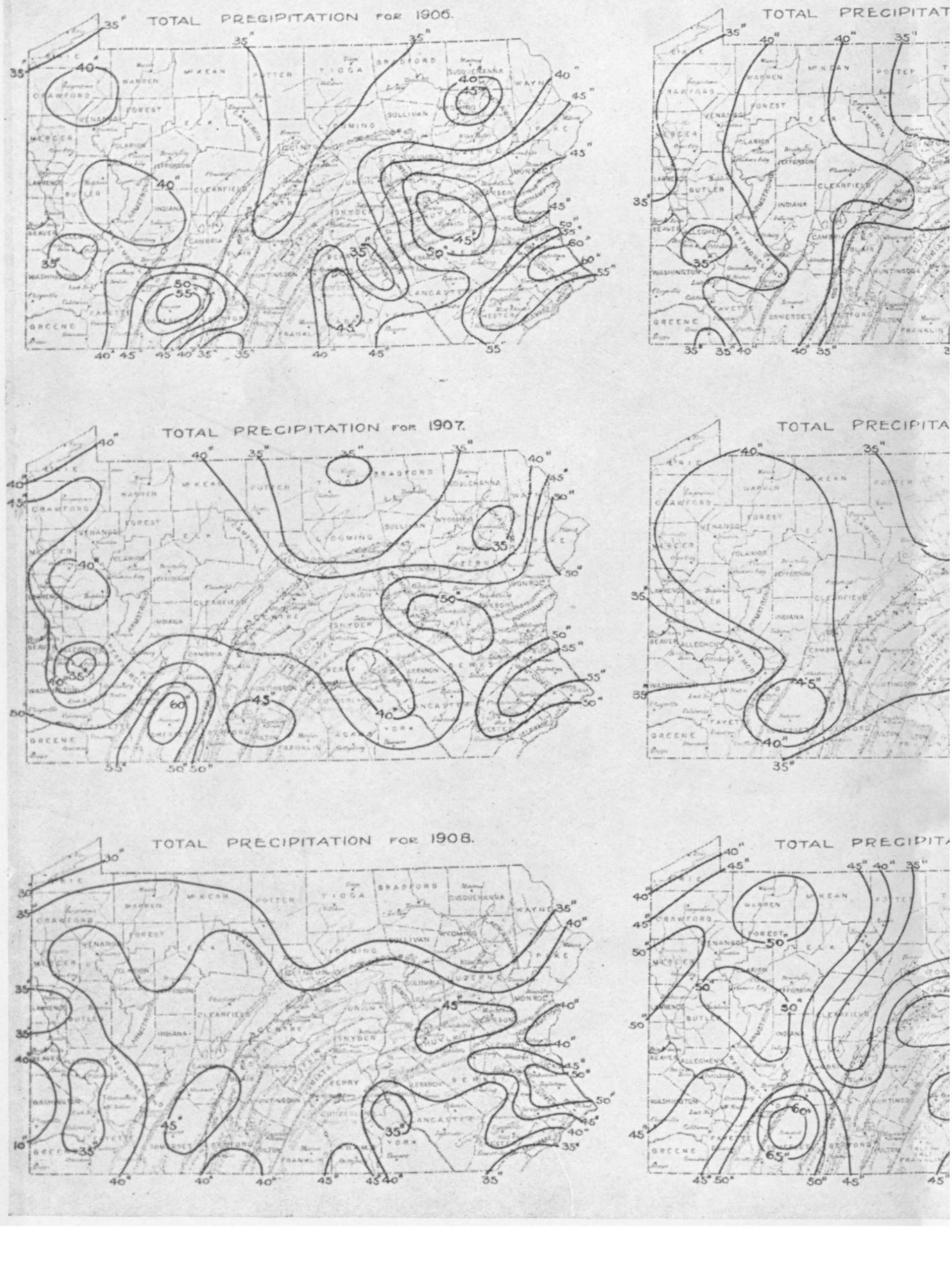
The above are some examples of extremes, and in many districts the proportion between maximum and minimum records covers a smaller range, being included between 150 and 200 per cent. The extreme ratios are limited to certain localities.

Of importance for certain hydraulic studies is the ratio of minimum to average annual total, which, though varying with the length of record and the characteristics of the period, mainly falls between the proportions of 40 and 60 per cent, there being also certain localities with their special conditions and relations.

The effect of single years and groups of years on even extended averages is illustrated by the following table.

Comparisons of annual depositions are best made when the distributions throughout the year are similar, as the time during which actual precipitation occurs is but a small proportion of the large unit of 8760 hours.

ANNUAL PREC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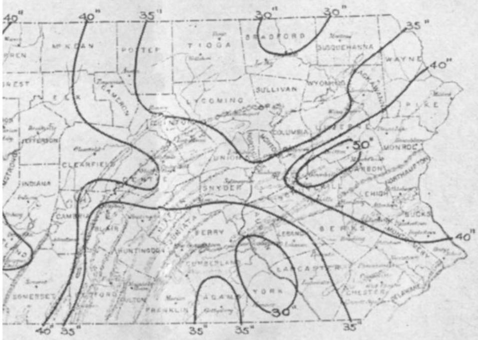
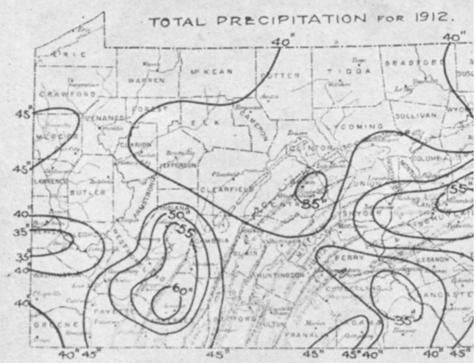
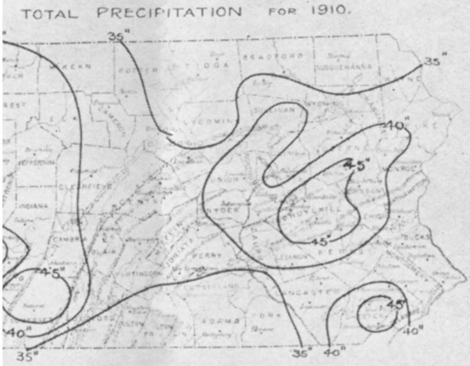
TOTAL PRECIPITATION FOR 1909.



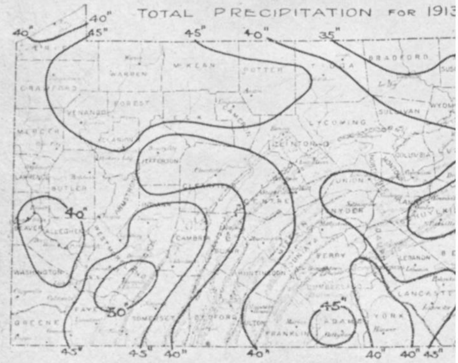
TOTAL PRECIPITATION FOR 1912.



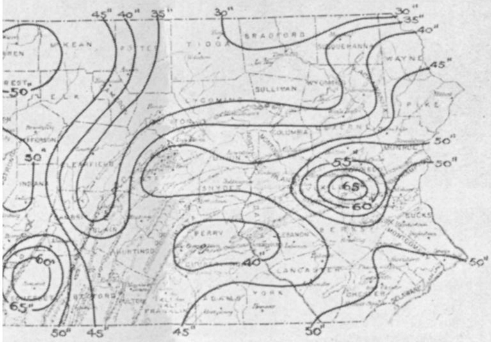
TOTAL PRECIPITATION FOR 1910.



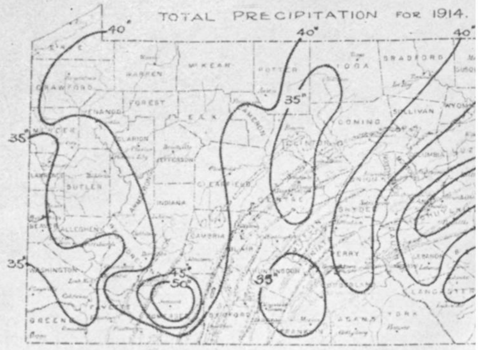
TOTAL PRECIPITATION FOR 1913



TOTAL PRECIPITATION FOR 1911.



TOTAL PRECIPITATION FOR 1914.



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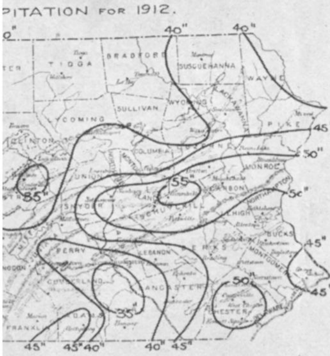
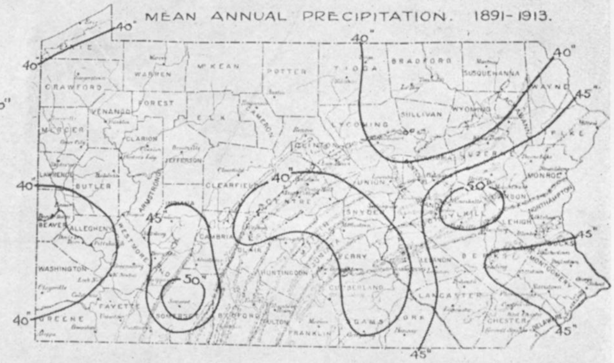
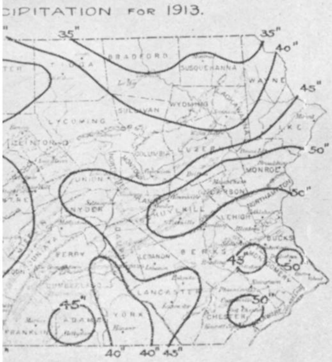


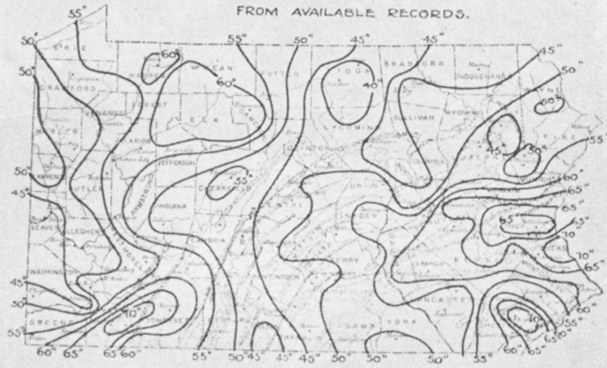
MEAN ANNUAL PRECIPITATION. 1891-1913.



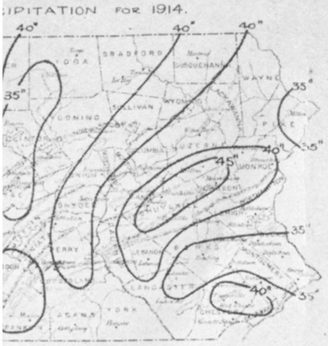
[PRE]CIPITATION FOR 1913.



OCCURENCE OF MAXIMUM PRECIPITATION.
FROM AVAILABLE RECORDS.



[PRE]CIPITATION FOR 1914.



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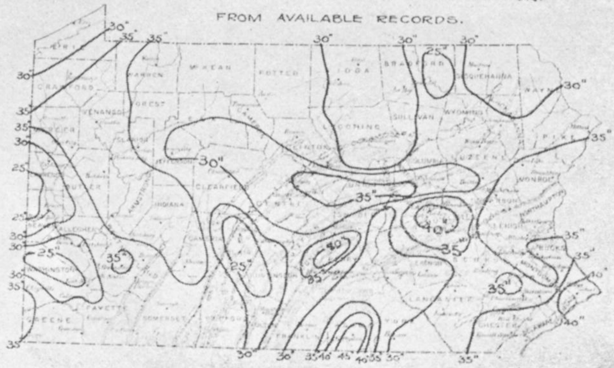


TABLE 2

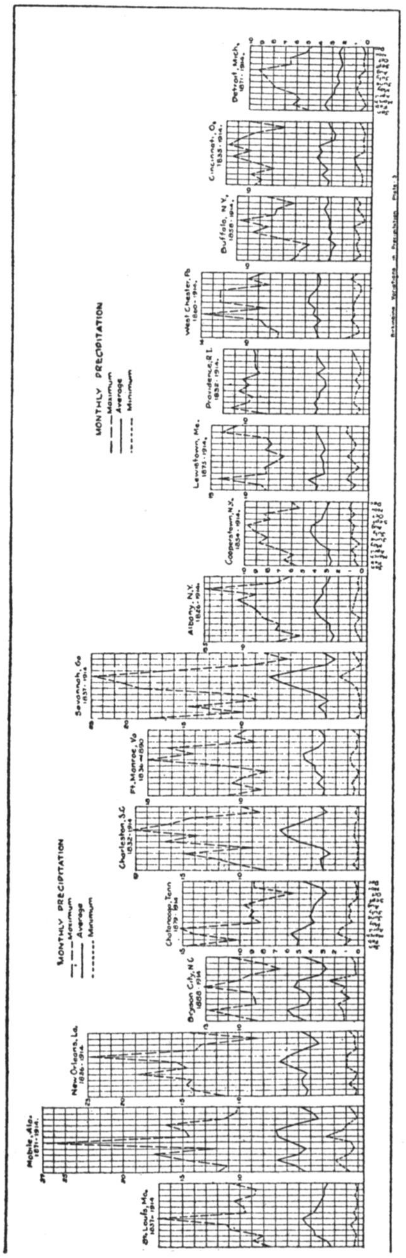
Monthly and annual averages of precipitation at Philadelphia, Pa., for different intervals

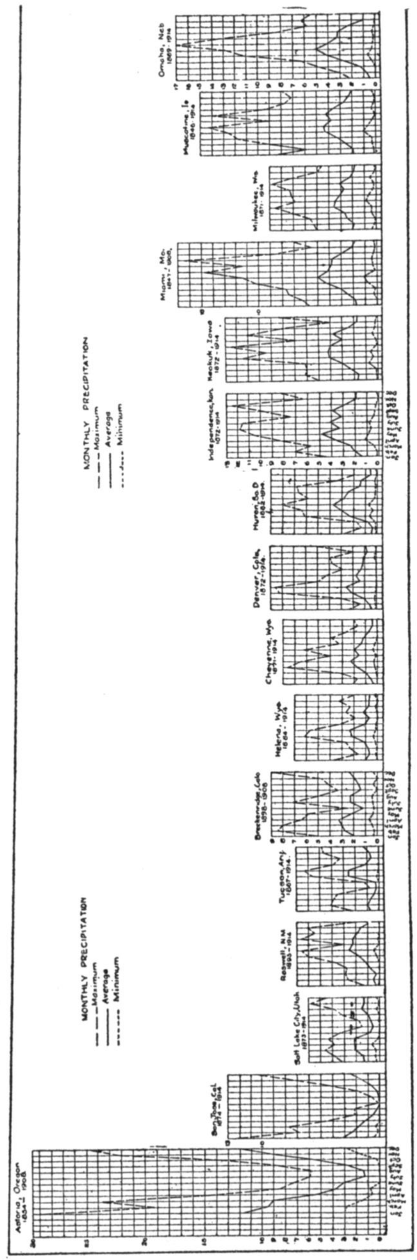
MONTHS	AVERAGE PRECIPITATION IN INCHES			
	Years 1895-1914	Years 1871-1914	Years 1860-1914	Years 1820-1914
January	3.13	3.26	3.34	3.25
February	3.33	3.31	3.41	3.32
March	3.71	3.54	3.65	3.41
April	3.37	3.05 min.	3.23	3.04
May	3.22	3.26	3.75	3.26
June	3.52	3.32	3.60	3.31
July	4.13	4.19	3.97	4.13
August	5.05 max.	4.77 max.	4.65 max.	4.73 max.
September	3.30	3.38	3.64	3.36
October	3.22	3.09	3.21 min.	3.03 min.
November	3.02 min.	3.15	3.29	3.13
December	3.69	3.21	3.28	3.13
Annual	42.70	42.07	43.02	41.66

MONTHLY PRECIPITATION

The month is convenient as a subdivision of climatic seasons or hydrologic periods, as well as for a unit in studying the relation between rainfall and runoff, but it is obviously too short an interval to estimate reliably for appreciable quantities, save where a distinct rainy season exists. Variations in total amounts deposited during the different months are graphically shown on plate 5; and plate 6 illustrates these divergences for one location. It is important in hydraulic studies to learn as far as possible the extremes which may occur in separate months, and the character of the occurrence of the precipitation, for these affect the capacity of storage and the provisions for excess water.

Overlappings of runoff ratios into the succeeding month are obviously more usual in large drainage areas, and in the smaller basins they can be discarded as exceptions or compensated. In addition to these, and the individual character of the watershed, the manner of occurrence is important, for this causes the disproportionate runoffs from falling and melting snow, and between moderate rains during the humid seasons and heavy downpours in short intervals during hot months. It is important to recognize the true value of


MONTHLY PRECIPITATION
Maximum
Average
Minimum


MONTHLY PRECIPITATION
Maximum
Average
Minimum

a monthly average, for quantities which can not be utilized because of their surplus are to be discarded, and a true usable average determined.

Abnormal monthly precipitation totals have, in many instances, represented a large proportion of the annual accumulation, and while a succession of two separate monthly maxima or minima has been instanced, in general the distributions of these extremes are well scattered.

Some chronicles have shown the years of greatest and least precipitation to contain no extreme record for any specific month, and a few examples are given.

TABLE 3

Occurrence of extreme monthly amounts in years of maximum and minimum precipitation

LOCATION	INTERVAL	MAXIMUM YEAR INCLUDED MAXIMUM MONTHLY RECORD OF	MINIMUM YEAR INCLUDED MINIMUM MONTHLY RECORD OF
Block Island, R. I.	1881–1914		
Boston, Mass.	1818–1914	July	
Chicago, Ill.	1871–1914	May and October	
Davenport, Iowa	1872–1914		August
Denver, Colo.	1872–1914	February and September	
Dubuque, Iowa	1851–1914	February	February and October
Indianapolis, Ind.	1872–1914		September
Nashville, Tenn.	1871–1914	February and October	
New Orleans, La.	1836–1914	February	
New York, N. Y.	1871–1914	July and November	
Oklahoma, Okla.	1891–1914	February, April and October*	July
Pittsburgh, Pa.	1872–1914	December	
Raleigh, N. C.	1887–1914		June
Richmond, Va.	1872–1914	April, May, June and July	January
Rochester, N. Y.	1871–1914	March and October	
St. Louis, Mo.	1837–1914	August	August
Salt Lake City, Utah	1875–1914	November	

* This year also included the minimum December record.

The charts of Mr. B. C. Wallis showing equipluves for each month and the regions in which specific months show the greatest and least water received indicate a variation in these that is dissimilar to records for the year and for precipitation in brief intervals.

The accompanying Table 4 indicates one instance of distribution, in which the year of maximum annual precipitation included no maximum month, and only one minimum monthly record occurred in the year of least precipitation. Two years experienced 2 of the maximum monthly records, one of these also including a minimum monthly, 2 years included a minimum monthly, of which 1 year also had a maximum for a month, and 4 other years gave both a maximum and minimum monthly record. In total the maximum and minimum monthly records were each distributed among 10 years, and 74 per cent of the years experienced one extreme of monthly total.

TABLE 4

Extremes of monthly precipitation at Williamsport, Pa, 1896–1914

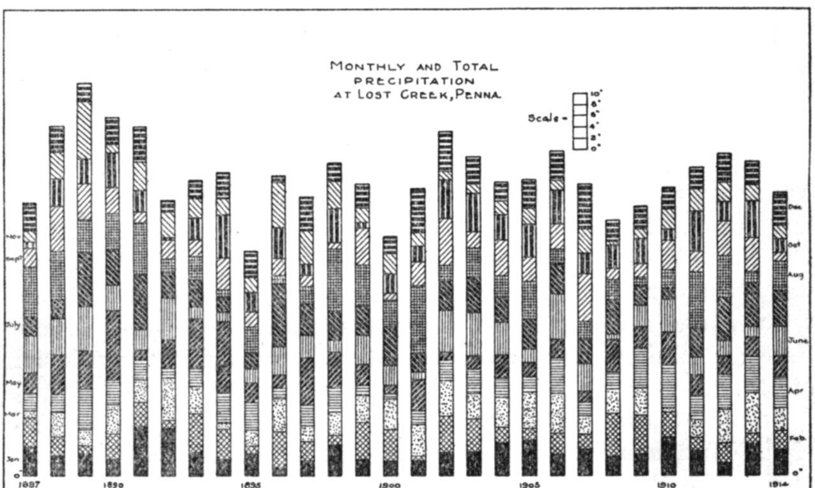
MONTH	MAXIMUM		MONTH	MINIMUM	
	Inches	Year		Inches	Year
January	4.25	1913	January	1.21	1912
February	5.08	1908	February	0.66	1901
March	5.11	1904	March	0.42	1910
April	8.22	1909	April	0.81	1900
May	6.34	1901	May	1.28	1911
June	7.16	1907	June	0.79	1912
July	8.01	1908	July	0.75	1909
August	9.65	1912	August	0.94	1907
September	5.65	1902	September	0.81	1898
October	5.92	1898	October	0.92	1910
November	3.46	1897	November	0.51	1904
December	6.05	1901	December	0.89	1896
Annual	43.64	1905	Annual	29.94	1900

EXTENSIVE PRECIPITATION

Not only for the much greater demands of industries are large streams and rivers drawn upon for water supply, but with the development of purification methods these furnish large quantities for general and domestic purposes. Where the usage is purely industrial an equal warrant for uninterrupted supply is less necessary

than when the health and safety of a community are considered, but the financial investment demands protection against excessive damage or destruction. On most large streams the demands for lower riparian rights, sanitation, and in some instances navigation, so restrict the allowable draft that minimum flow conditions do not limit the supply. Flood conditions may damage structures or equipment, and affect existing mains.

In general, severe floods from large drainage basins are due to excessive rainfall. Aside from the quantity of rain and character of basin the effect is modified by dry, hard, moist, saturated or frozen



Birkinbine Variations in Precipitation Plate - 6.

ground, and frozen or melting snow. But a large number of severe floods have been caused by rainfall only, occurring at a season when absorption by air and vegetation is high. The most severe flood on the Schuylkill River in Pennsylvania occurred in early September, 1850, and on October 4 and 5, 1869, was registered the second highest flood conditions on the upper river and the maximum heights on the lower reaches.

The Passaic River in New Jersey, in October, 1903, reached extreme flood stages, and the rainfall records are notable for the severity. Mr. C. C. Vermeule computed the average rainfall on the watershed, based on 11 stations, to be:

October 8	2.21 inches
October 9	7.83 inches
October 10	1.55 inch
October 11	0.39 inch
	11.98 inches

Individual stations reported quantities from 9¾ inches to 15½ inches for the 4 days, and among the rainfalls were:

Newark, 68½ hours	11.83 inches
Ringwood, 33 hours	10.63 inches
Essex Falls, 48 hours	10.66 inches

while 24 hour amounts reached 11.45 inches at Paterson, and above 8 inches at 3 other stations on the watershed, and many others received from 6 inches to 8 inches.

This rainfall was remarkable, not only for its continuance and severity, but also because of its intensity for some intervals, New York City recording 2.42 inches in 2 hours, and Newark 1.20 inches in 1 hour; and of the large area affected. The average precipitation for New Jersey, for this month, and nearly all of which fell during this storm, was nearly 2½ times the normal. Adjacent areas were affected, and not only did small streams overflow, but the Delaware River at Phillipsburg and Lambertville reached its maximum crests.

Another feature of note is that this followed a summer of precipitation above normal, which was reflected in the water content of the ground. As a result, the 1903 storm, according to Mr. Vermeule, produced a runoff on the Passaic basin of nearly 60 per cent, more than twice the proportion from the rains of September 1882; for, although the earlier occasion gave a greater total precipitation, it followed a summer of deficient rain.

The floods on the Saginaw and Grand Rivers, Michigan, in May 1912; on the Wisconsin River at Wausan in July 1912; and the Cherry Creek flood at Denver, July 14 1912, are respective examples of continued rains covering a number of days, of severe rain within a calendar day, and of an intense storm in a short interval.

The most pronounced instance of excessive rain over an extended area is the Ohio Valley disaster of 1913. While the runoff was intensified by the moist condition of the soil, there were fortunately no material quantities of snow on the higher areas, and the unusual

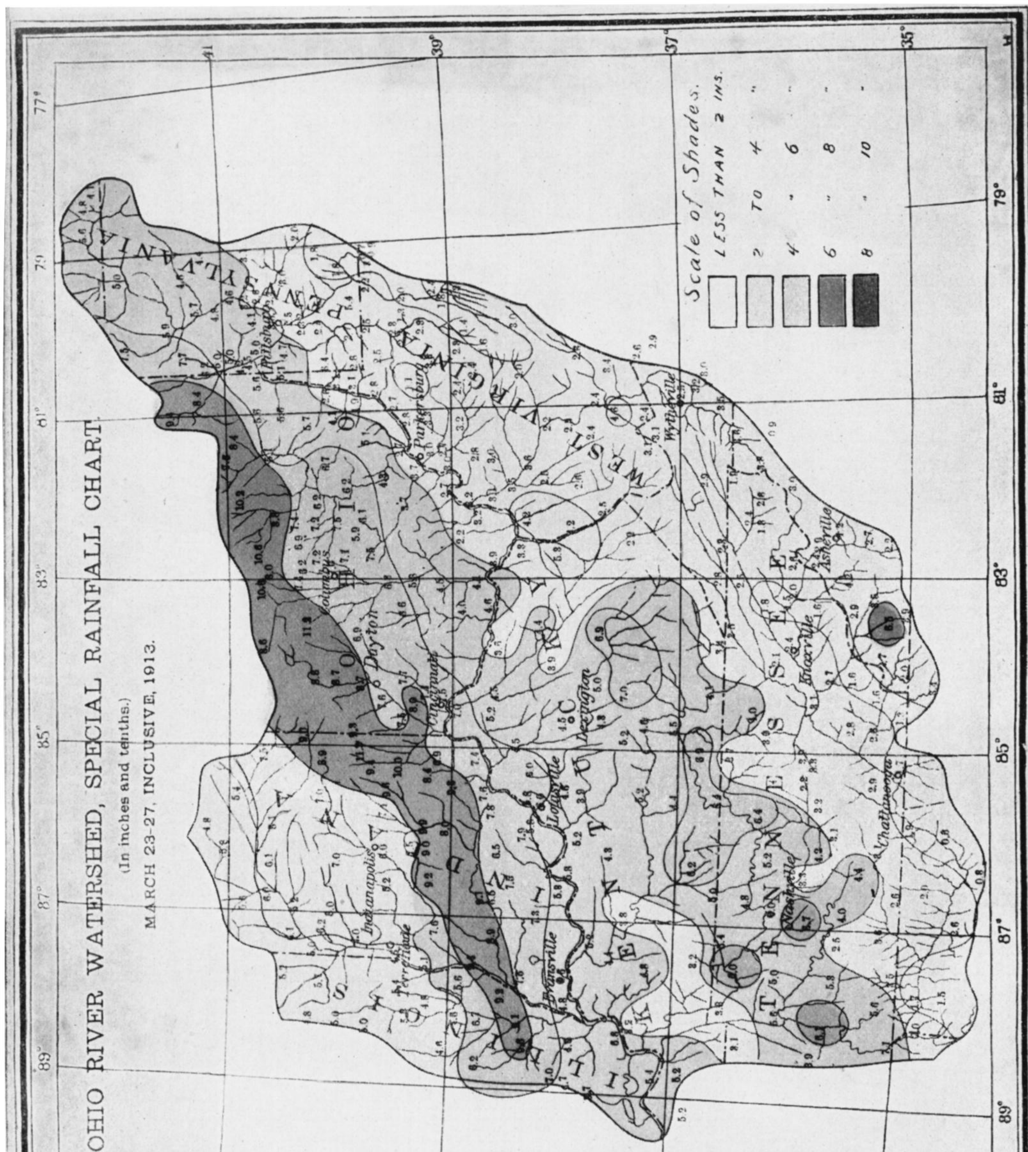
rainfalls due to different storms in close succession are shown on plate 7, while 6.66 inches in 1 day, Shoals, Indiana, March 25, and 9.20 inches in 3 days, Bellefontaine, Ohio, illustrate the intensity of rainfall at times. Heavier 24-hour and 72-hour totals have been recorded for the affected region, but the total area covered by extreme rains has not been equalled since records have been kept.

Prof. J. Warren Smith has calculated that the 5-day rainfall on 9 watersheds, draining from 1025 to 7693 square miles, ranged from 6.94 inches, on the largest of these basins, to 8.68 inches, on an area of 1567 square miles, giving total depositions of from 15,000,000 to 20,000,000 cubic feet per square mile. Prof. A. J. Henry estimated the total excess discharge at Parkersburg, West Virginia, due to an average rainfall on the watershed of 4.7 inches as nearly 300,000 million cubic feet.

The latter part of March 1913, also witnessed abnormal rainfalls which established new flood records on the Genesee River at Rochester, on the Hudson River at Mechanicville and Albany and on many tributaries; and severe floods occurred on the Connecticut River, producing the maximum recorded stage at Brattleboro, Vermont. The conditions extended to other states, it being the wettest March in Ohio, Indiana, New York, Pennsylvania, South Carolina, Georgia and Alabama, and unusual quantities fell at adjoining localities.

The flood of 1889, which devastated Johnstown, Pennsylvania, and established record flood heights on the Susquehanna River, was caused by the unusual quantities of precipitation. Mainly the heaviest rains occurred on May 31, though 40 stations received rain on June 1, while 22 of these showed more than 1 inch, and 4 had more than 3 inches on that day. This storm was marked by some severe downpours, Grampian Hills having 6 inches in 7 hours and Harrisburg 8 inches in 18 hours. No rain was noted on June 2, but this month was characterized by frequent and heavy rainfalls, the average for Pennsylvania stations being 15 days with rain and 5.43 inches total.

Frequent rains, each of moderate amount, have produced damaging floods by so saturating the soil and filling water courses that the later rains became a direct runoff. Flood channel and spillway design are contingent on such conditions, the latter requiring not only ample width and depth, stability, and shape of crest, but also proper design of rollway, that the passage of water over the face will



Birkinbine. Variations in Precipitation. Plate.-7.

follow proper lines, but the apron must be so laid out that water discharging from it will not undercut the structure or erode the river bottom, and thus set up damaging currents. Flood conditions, especially when occurring at the close of winter, frequently produce in reservoirs an upper stratum of water that demands purification because the continuous excess inflow carries the washings from the watershed.

DAILY PRECIPITATION

The precipitations in brief intervals are important because of the large quantities sometimes deposited. The actual duration of the reception of moisture is generally much less than 24 hours, which is merely a unit of interval. In fact the actual total period of precipitation is for many localities but a small portion of the day.

Plate 10 illustrates some instances of the proportion which unusual excessive daily amounts bear to the monthly and annual totals, and they have been grouped so as to show the relative importance of these daily measures.

The effect of daily quantities upon turbidity is illustrated on plate 9, compiled by courtesy of the Water Department of Reading, Pennsylvania. The low and constant turbidity in the early and late months of the year was due to the precipitation during these intervals being mainly frozen; and small variations in turbidity in portions of November and December are explained by low temperature and moderate rate of precipitation. The high turbidities following the rains of June 2 (0.75 inch) and August 10 (1.08 inch), and the lower degree subsequent to the rains of June 6 (1.60 inch), July 11 (2.68 inches and preceded by 1.15 inch on the previous day), September 24 (2.26 inches), and October 23 (1.92 inch), can be explained by differences in intensity of precipitation.

Continuous precipitations for more than a day give small totals except when caused by a succession of storms. They are infrequent, save where a marked rainy season occurs.

CONTINUOUS PRECIPITATION

Precipitations of continued duration must be defined by their intensity and by local rainfall characteristics. Galveston affords some examples of what may be termed almost tropical rainfalls, one of which is illustrated on plate 14, and the Gulf region is subjected to

PLATE 10

Some twenty-four hour precipitations and their relation to total monthly and annual amounts. All quantities in inches

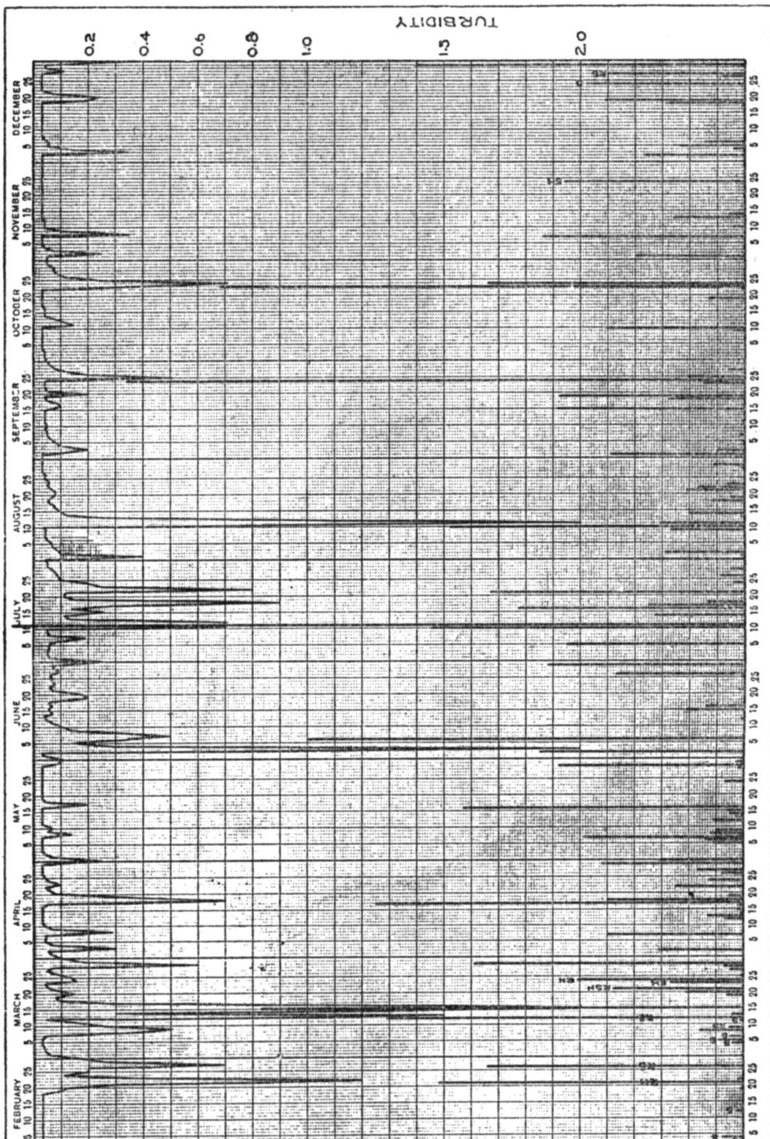
LOCATION	DATE	TOTAL PRECIPITATION IN		
		Twenty-four hours	Month	Year
Atlantic City, N. J.	October, 1903	9.21	12.13*	61.11
Columbia, Mo.	September, 1905	6.13	11.54*	47.03
Evansville, Ind.	October, 1910	6.94	11.19*	45.46
Galveston, Tex.	July, 1900	14.35	18.74*	69.66
Galveston, Tex.	October, 1901	14.10	15.00*	51.33
Jacksonville, Fla.	May, 1903	9.06	14.80*	52.03
Knoxville, Tenn.	September, 1898	5.68	7.44*	42.79
Little Rock, Ark.	April, 1913	9.58	11.46*	61.57
La Crosse, Wis.	October, 1900	7.23	12.09*	41.85
Lynchburg, Va.	October, 1902	7.18	9.86*	48.79
Montgomery, Ala.	January, 1892	9.98	17.78*	69.85
New York, N. Y.	October, 1903	9.40	11.55*	48.60
New Orleans, La.	March, 1903	8.66	14.61*	57.18
Pensacola, Fla.	September, 1906	7.68	16.48*	47.05
Savannah, Ga.	August, 1910	8.56	11.75*	46.61
Topeka, Kan.	September, 1909	8.08	11.48	46.96
Vicksburg, Miss.	March, 1902	7.12	12.96*	47.31
Washington, D. C.	September, 1904	5.00	5.34*	40.84
Cambridge, Ohio	July, 1914	7.09	8.36*	44.42
Concordia, Kan.	July, 1907	5.69	5.91*	24.05
Corpus Christi, Tex.	February, 1893	5.80	6.27*	20.50
Davenport, Ia.	June, 1905	5.06	7.68*	31.54
Fort Smith, Ark.	April, 1893	4.98	7.89*	44.70
Galveston, Tex.	April, 1904	9.23	11.04*	42.65
Indianapolis, Ind.	September, 1895	6.80	7.46*	33.54
Kansas City, Mo.	July, 1896	5.62	8.66*	33.64
Kearney, Neb.	May, 1893	3.72	7.49*	22.86
Lincoln, Neb.	August, 1910	8.38	14.21*	31.33
Madison, Wis.	August, 1906	5.07	7.56*	32.38
Moorhead, Miss.	June, 1894	4.08	7.70*	22.43
Omaha, Neb.	August, 1903	7.03	12.50*	33.43
Shreveport, La.	December, 1904	7.18	9.62*	35.29
St. Paul, Minn.	July, 1892	5.67	9.04	32.55
San Luis Obispo, Cal.	January, 1901	5.04	11.21*	25.76
Topeka, Kan.	October, 1912	5.70	7.05*	31.92
Yankton, S. D.	July, 1900	7.52	13.27*	31.38

* Indicates highest monthly total in the year.

PLATE 10—Continued

LOCATION	DATE	TOTAL PRECIPITATION IN		
		Twenty-four hours	Month	Year
Amarillo, Tex	July, 1910	2.17	3.57*	11.15
Bismarck, N. D	September, 1894	3.67	3.83*	14.32
Boise, Id	March, 1904	2.46	5.39*	14.08
Cheyenne, Wyo	July, 1896	4.70	6.35*	20.79
Dodge City, Kan	July, 1893	2.05	3.32*	10.12
Los Angeles, Cal	May, 1898	1.46	1.75*	4.83
Los Angeles, Cal	November, 1900	3.79	6.53*	11.30
Modena, Utah	July, 1907	2.17	2.46*	12.80
North Platte, Neb	June, 1894	1.94	3.54*	11.21
Oklahoma, Okl	April, 1910	3.75	4.31*	17.27
Pierre, S. D	June, 1895	3.32	6.09*	16.85
Pueblo, Colo	May, 1894	2.48	3.76*	12.64
Rapid City, S. D	May, 1899	4.24	6.76*	16.71
Salt Lake City, Utah	May, 1901	2.72	4.27*	16.08
Santa Fe, N. M	September, 1904	2.51	5.37*	14.19
St. Paul, Minn	May, 1910	1.37	1.76*	10.21
Sioux City, Ia	April, 1913	3.08	5.50*	20.31
Walla Walla, Wash	May, 1906	2.74	4.81*	19.13
Brawley, Cal	August, 1909	1.22	1.43*	3.69
Carson City, Nev	March, 1903	1.34	1.56	6.23
Del Rio, Tex	April, 1910	2.52	3.30*	9.06
Denver, Colo	May, 1893	1.41	3.09*	8.48
El Paso, Tex	June, 1910	1.02	1.35*	4.03
Havre, Mont	June, 1895	1.70	3.36*	10.94
Independence, Cal	February, 1902	1.41	1.69*	3.83
Independence, Cal	September, 1910	0.72	0.72*	2.37
Miles City, Mont	August, 1900	3.36	4.58*	10.55
Phoenix, Arix	February, 1901	0.80	1.46	4.87
Phoenix, Ariz	September, 1903	1.72	3.16*	6.61
Reno, Nev	July, 1910	1.20	1.45*	5.97
Reno, Nev	August, 1912	0.96	0.96*	4.66
Roswell, N. M	August, 1910	1.01	2.03*	4.87
Tonopah, Nev	May, 1913	0.86	1.11	6.75
Yuma, Ariz	March, 1893	0.54	1.29*	3.00
Yuma, Ariz	November, 1899	0.50	0.50*	0.60
Yuma, Ariz	August, 1909	4.01	6.25*	8.63

* Indicates highest monthly total in the year.


RAINFALL AND TURBIDITY. MAIDEN CREEK, READING, PA. 1912.
TURBIDITY
0.2
0.4
0.6
0.8
1.0
1.5
2.0
JANUARY
FEBRUARY
MARCH
APRIL
MAY
JUNE
JULY
AUGUST
SEPTEMBER
OCTOBER
NOVEMBER
DECEMBER
2.5
2.0
1.5
1.0
0.5
0
INCHES PRECIPITATION.
Birkinbine. Variations in Precipitation. Plate.-9

continuous rainfalls which are unknown to many other localities; Austin, Texas, being said to have had a 64-hour rainfall in July, 1869. The Pacific Coast, with its distinct winter season, is also subject to rains of extended duration.

It is not important whether an extended rainfall is entirely continuous or is broken by small intervals of no deposition, for any excess of water on saturated ground will produce high runoffs. But the distinction between the combined rainfall of several severe storms and continuous moderate rains is illustrated by the accompanying Table 5 of some rains in Baltimore, Maryland, which has experienced several severe storms of brief duration and great intensity.

TABLE 5

Some continuous precipitations at Baltimore, Md.

DATE	HOURS DURATION	TOTAL PRECIPITATION IN INCHES	AVERAGE RATE PER HOUR IN INCHES
April 19–21, 1893	44	1.14	0.026
April 10–12, 1894	52	1.95	0.036
December 10–12, 1894	49	2.01	0.041
January 8–10, 1895	55	1.55	0.028
April 27–May 1, 1895	102	3.69*	0.036
November 24–25, 1895	42	0.13	0.003
December 3–5, 1897	44	1.18	0.027
February 18–21, 1898	47	1.18	0.025
December 3–4, 1898	44	1.27	0.03
February 11–13, 1899	54	1.56	0.029
February 16–17, 1900	41	0.40	0.01
February 20–22, 1902	51	2.53	0.05
November 24–26, 1902	44	1.60	0.036
April 13–15, 1903	43	1.68	0.039

* At times the rate was excessive.

Professor Fassig listed 14 rain and snow storms of long duration at Baltimore for the period from April 1893, to April 1903, of which he says: "In these storms the rainfall was practically continuous, although in most of them there were intervals of a few hours during which only light sprinkling or misting rains were recorded."

INTENSE STORMS

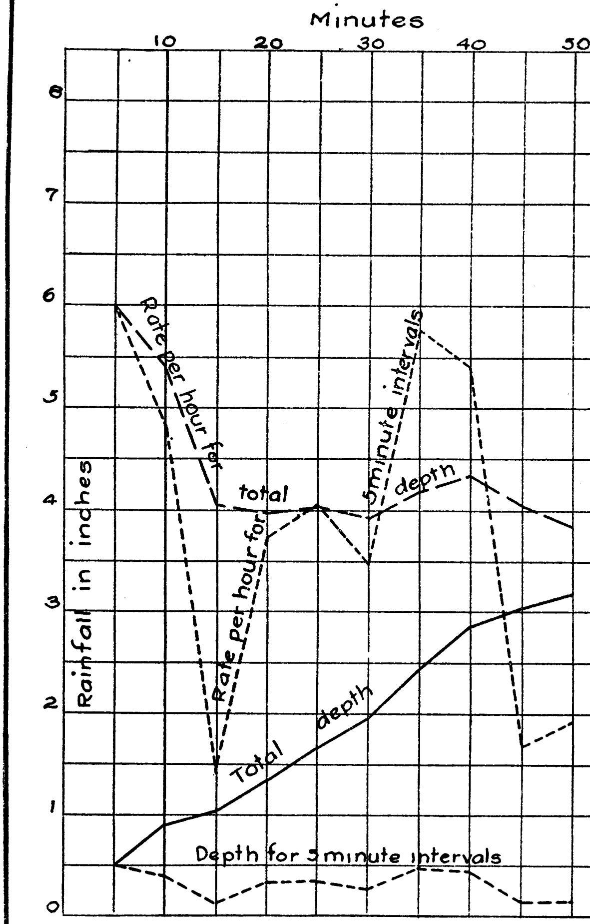
It is fortunate that the intensity of rainfall decreases with its duration, but the severity of local storms cause much damage. Many maximum 24-hour precipitations actually occur, most or all, in a few hours, and their geographic distribution differs widely from that of total annual precipitation.

The relative value of amounts deposited is important, for an extraordinary rain in some regions would not be considered unusual in other localities. On February 26, 1914, at Los Angeles, California, a precipitation of 2 inches in 2 hours overtaxed the street drainage system; the destructive flood of January 14, 1903, at Heppner, Oregon, which cost 200 lives, was due to an estimated fall of 1½ inch in 30 minutes over 21 square miles; and 0.76 inch in one hour at Pocatello, Idaho, on June 8, 1912, was but 0.01 inch below the record for such an interval.

Intense storms over small drainage areas have given the maximum runoff records, and it is unfortunate from the standpoint of information that in so many cases either or both rainfall and runoff records are not available. It is to be noted that such rains usually occur at a season when high temperatures of earth and air, and the growing state of vegetation, exert their influences in absorbing moisture. Such storms are of slight value in repletion of subsurface waters, the water being mainly carried away by direct runoff, hence but a small portion of it benefits underground reserves.

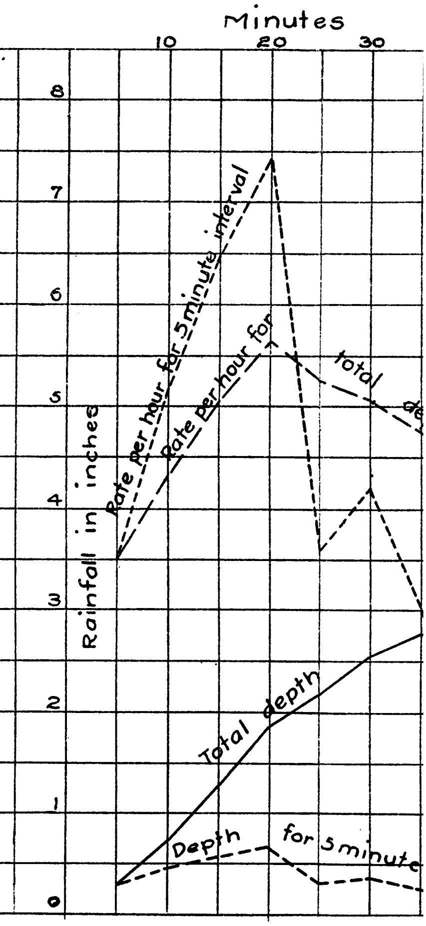
Plates 11 to 14 illustrate the quantities and rates of rainfall for the total period and for 5 minute intervals, as far as they are available, for various storms at different localities, as measured by recording gauges. These illustrate graphically, in different instances, the varying rates of intensity, the occurrence of more than one peak in the rate, the growing or decreasing severity as the storm continues, and the high rates reached at intervals. Some of such variations of high rates after the storm has been in progress are especially unfavorable, for 2 inches in 30 minutes is more severe when half of it falls in the last third of the period.

Such storms may entirely cover a small drainage area, and the duration of the downpour, the limited extent of the watershed or its configuration, may, singly or in combination, produce concentrated runoffs that fall into a special class because of their magnitude, and require estimation similar to storm water flow for cities.



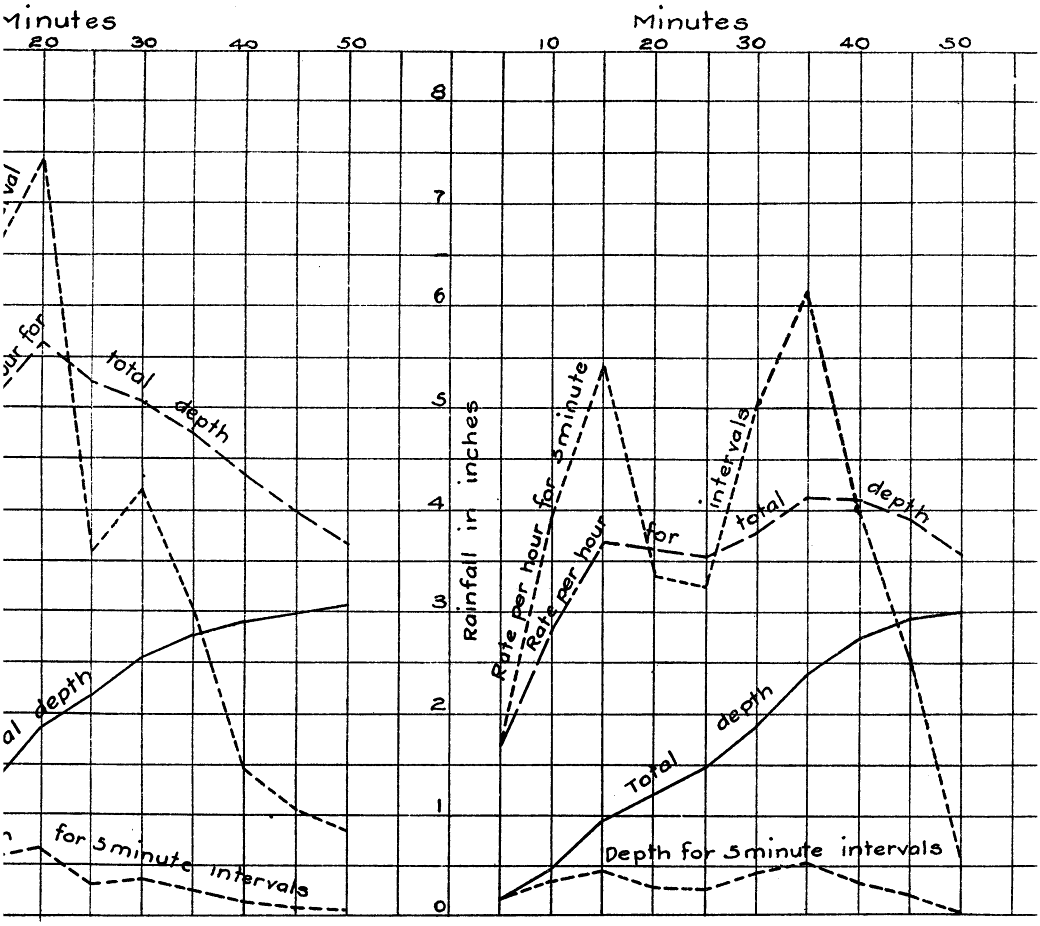
Rainfall at Atlanta, Ga Aug. 20, 1914.
9.54 A.M. to 10.45 A.M.

Maximum Precipitation
In 5 minutes = 0.50
In 10 minutes = 0.93.
In 15 minutes = 1.22



Rainfall at
Lincoln, Nebraska. July
5.29 P.M. to 6.19

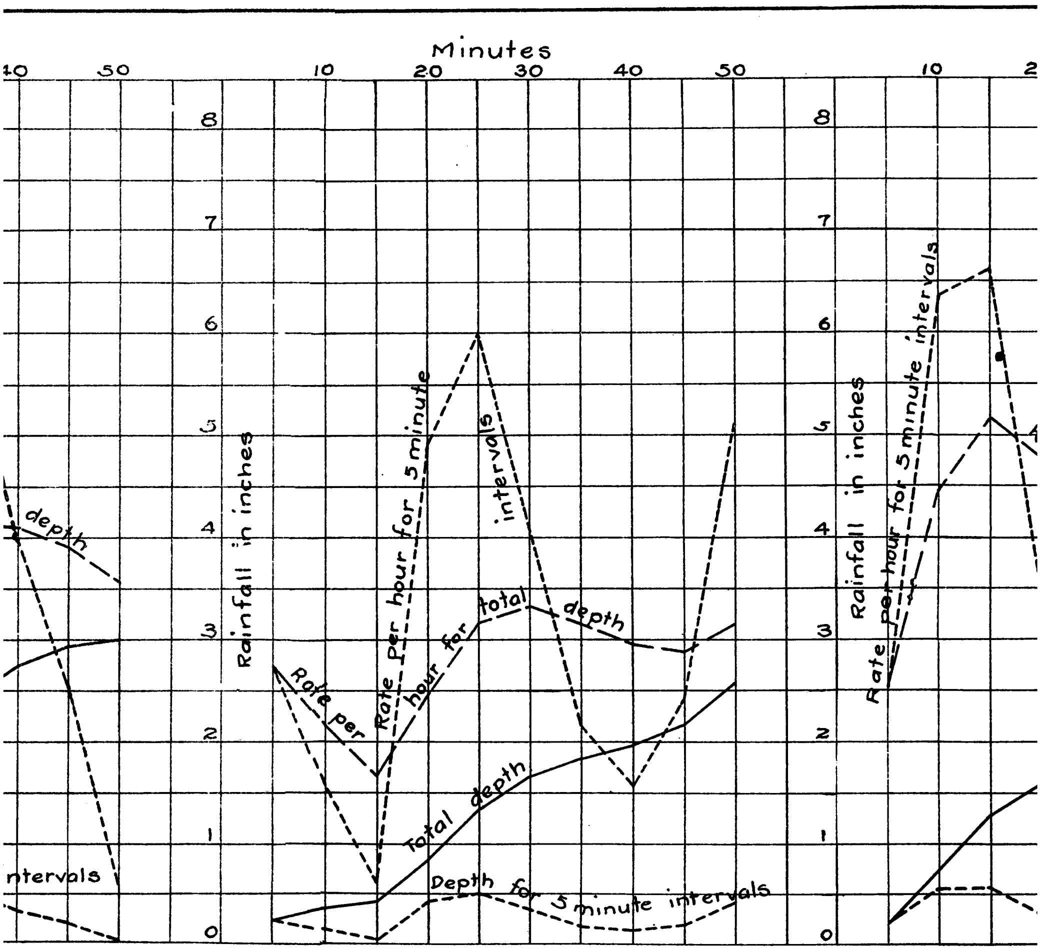
Maximum Precipitation
In 5 minutes = 0.
In 10 minutes = 1.
In 15 minutes = 1.



fall at
braska. July 25, 1914.
P.M. to 6.19 P.M.
minutes = 0.62
minutes = 1.16
5 minutes = 1.59

Rainfall at Bismarch, N.D. Aug. 9, 1909.
10.53 P.M. to 11.41 P.M.

Maximum Precipitation
In 5 minutes = 0.51
In 10 minutes = 0.93
In 15 minutes = 1.26



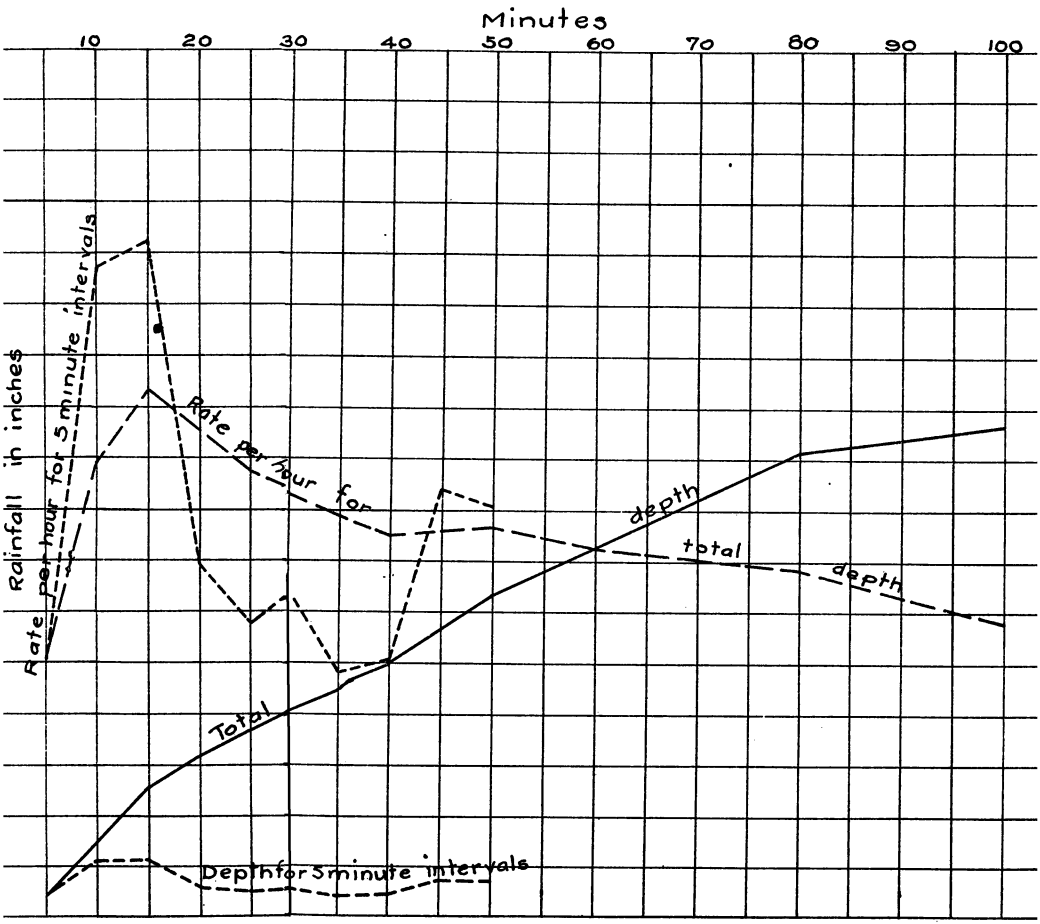
Aug.9,1909.

M.

Rainfall at Wichita Kansas, Sept.17, 1905.
8.25 P.M. to 9.17. P.M.

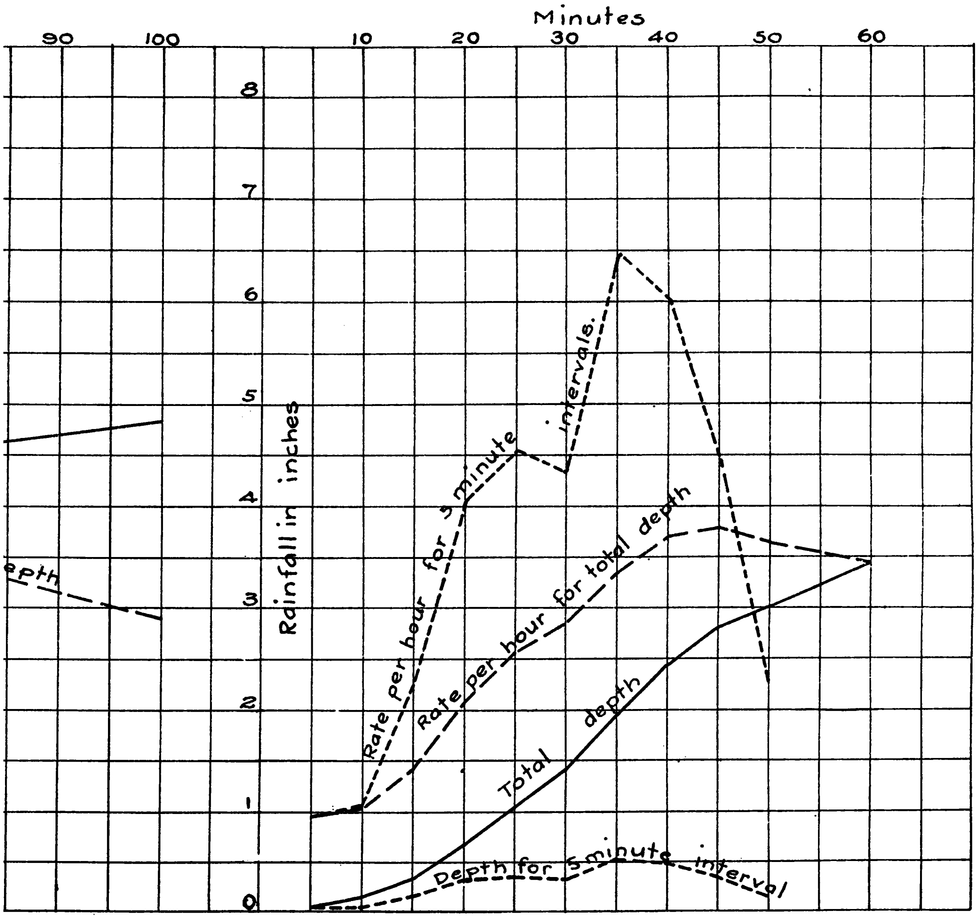
1	Maximum Precipitation	In 5 minutes = 0.50
3		In 10 minutes = 0.91
6		In 15 minutes = 1.25

Maxi
Precip



Rainfall at Madison Wisconsin, August 8, 1906.
5.24 P.M. to 6.56 P.M.

Maximum Precipitation
In 5 minutes = 0.55
In 10 minutes = 1.08
In 15 minutes = 1.37

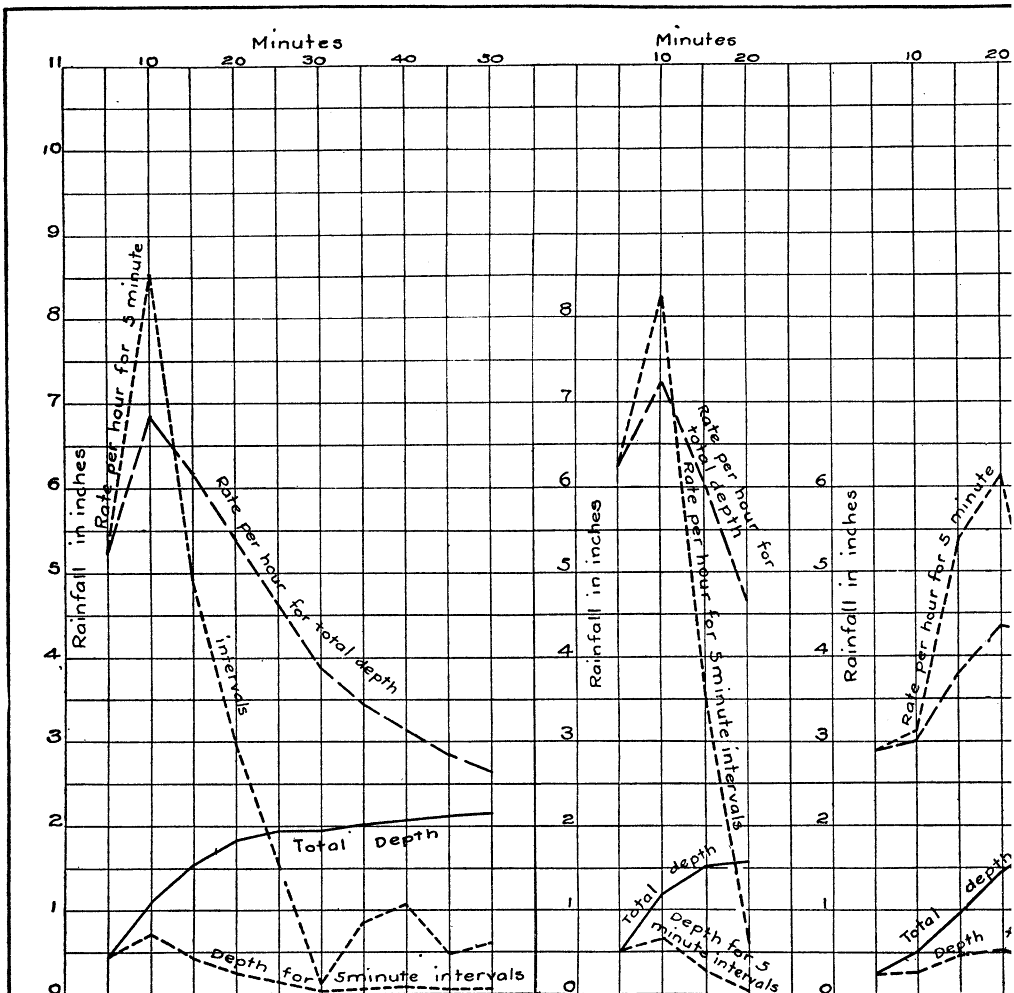


1906.

Rainfall at Montgomery Ala. May 30,1905.
10.38 A.M to 11.39 A.M.

Maximum Precipitation
In 5 minutes = 0.54.
In 10minutes = 1.04
In 15minutes = 1.41

PLATE 11



Rainfall at Saginaw, Mich. July 27, 1913.
3.33 P.M. to 4.21 P.M.

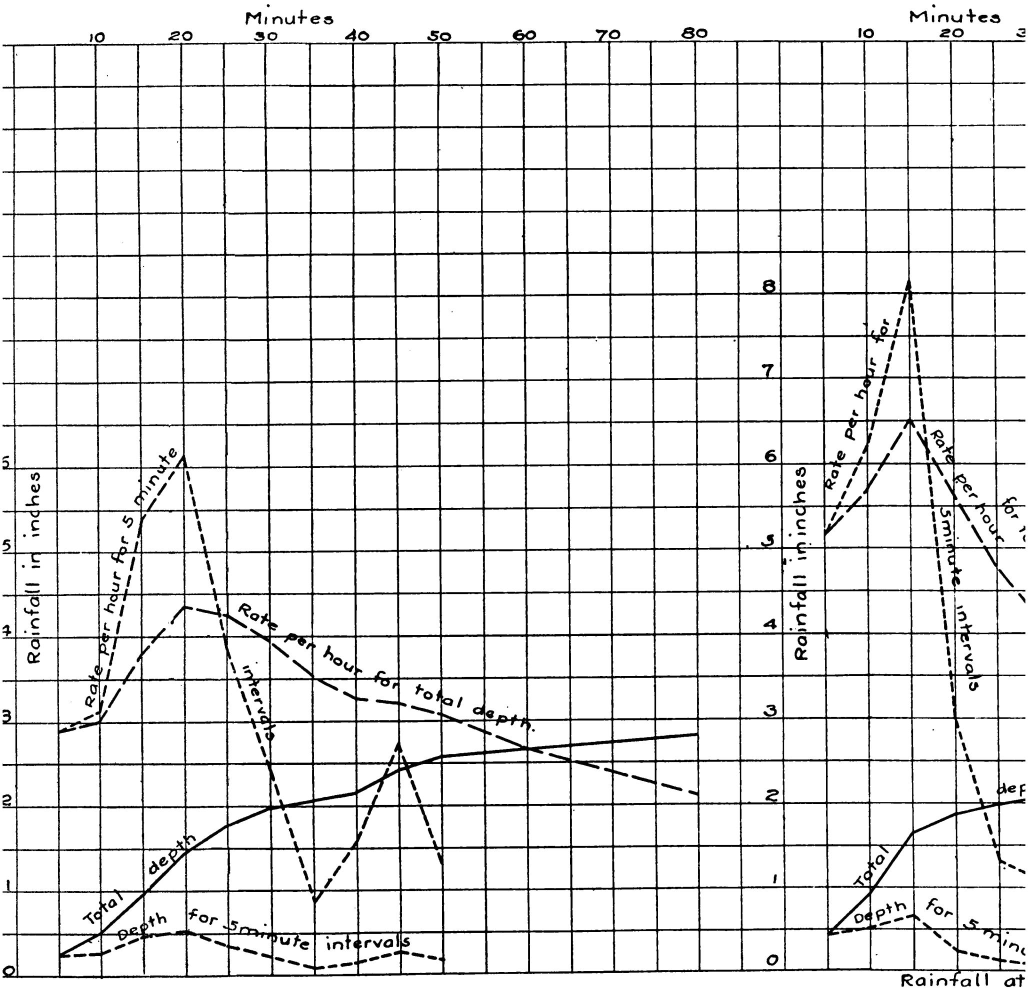
Maximum Precipitation
In 5 minutes = 0.71
In 5 minutes = 1.14
In 15 minutes = 1.55

Rainfall at Washington D.C.
July 30, 1913. 3.10 to 3.27 P.M.

Maximum Precipitation
In 5 minutes = 0.69
In 10 minutes = 1.21

Rain

Maximu
Precipita



Rainfall at Indianapolis, Ind. August 13, 1913.
11.55 A.M. to 1.01 P.M.

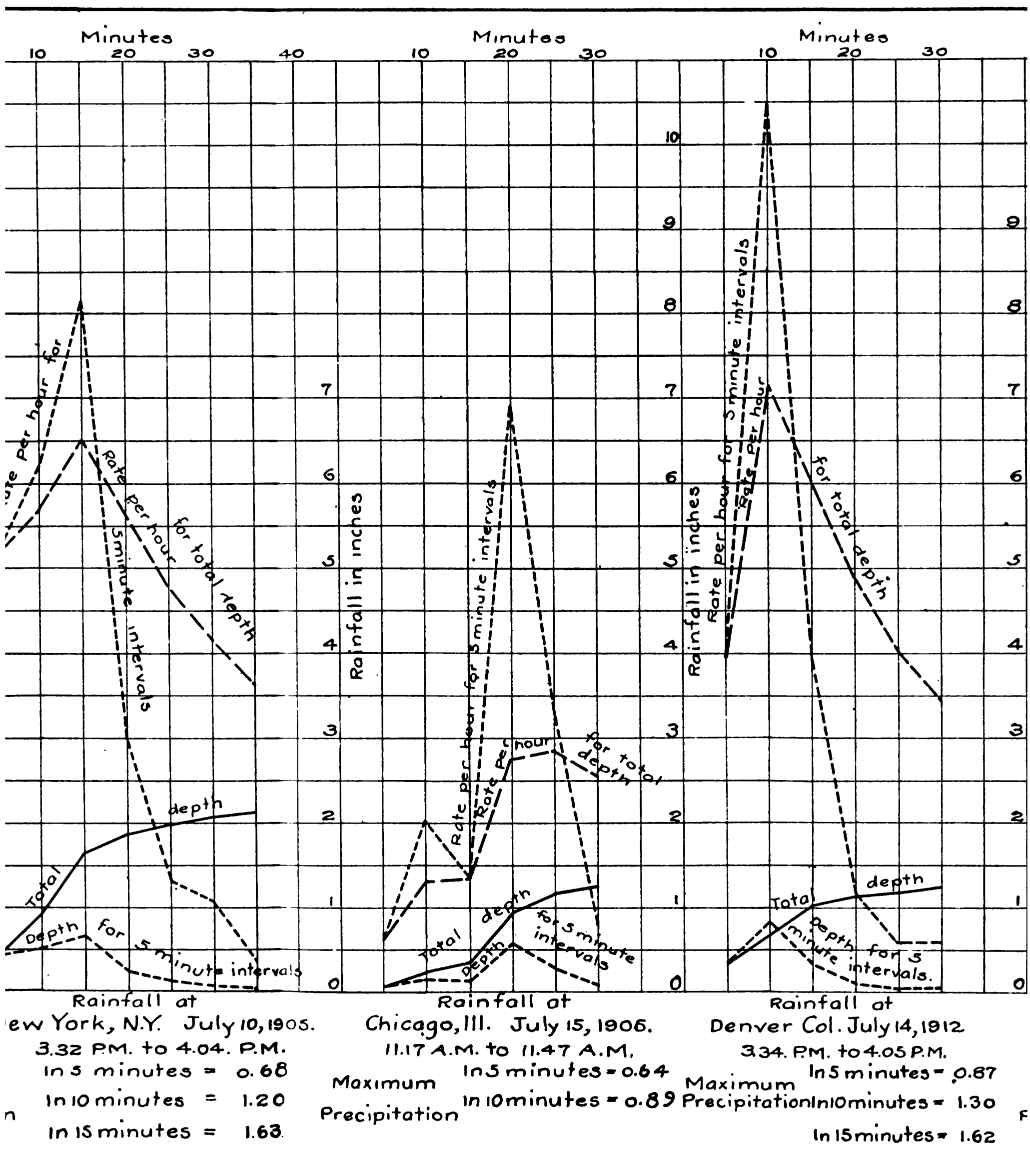
P.M.
0.69
1.21

Maximum Precipitation
In 5 minutes = 0.51
In 10 minutes = 0.96
In 15 minutes = 1.28

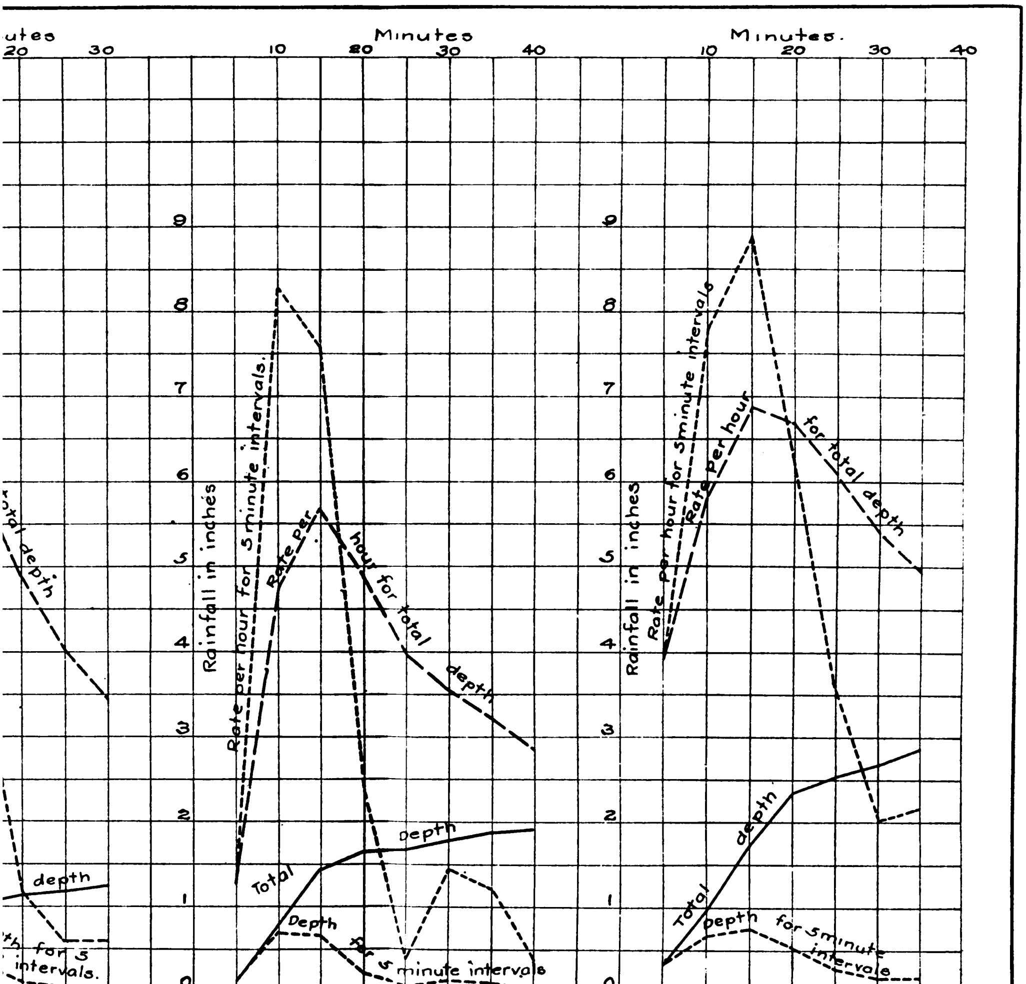
Rainfall at
New York, N.Y. J
3.32 P.M. to 4.

Maximum Precipitation
In 5 minutes
In 10 minutes
In 15 minutes

INTENSE STORMS



INTENSE STORMS



all at
. July 14, 1912
to 4.05 P.M.
minutes = 0.87
0 minutes = 1.30
15 minutes = 1.62

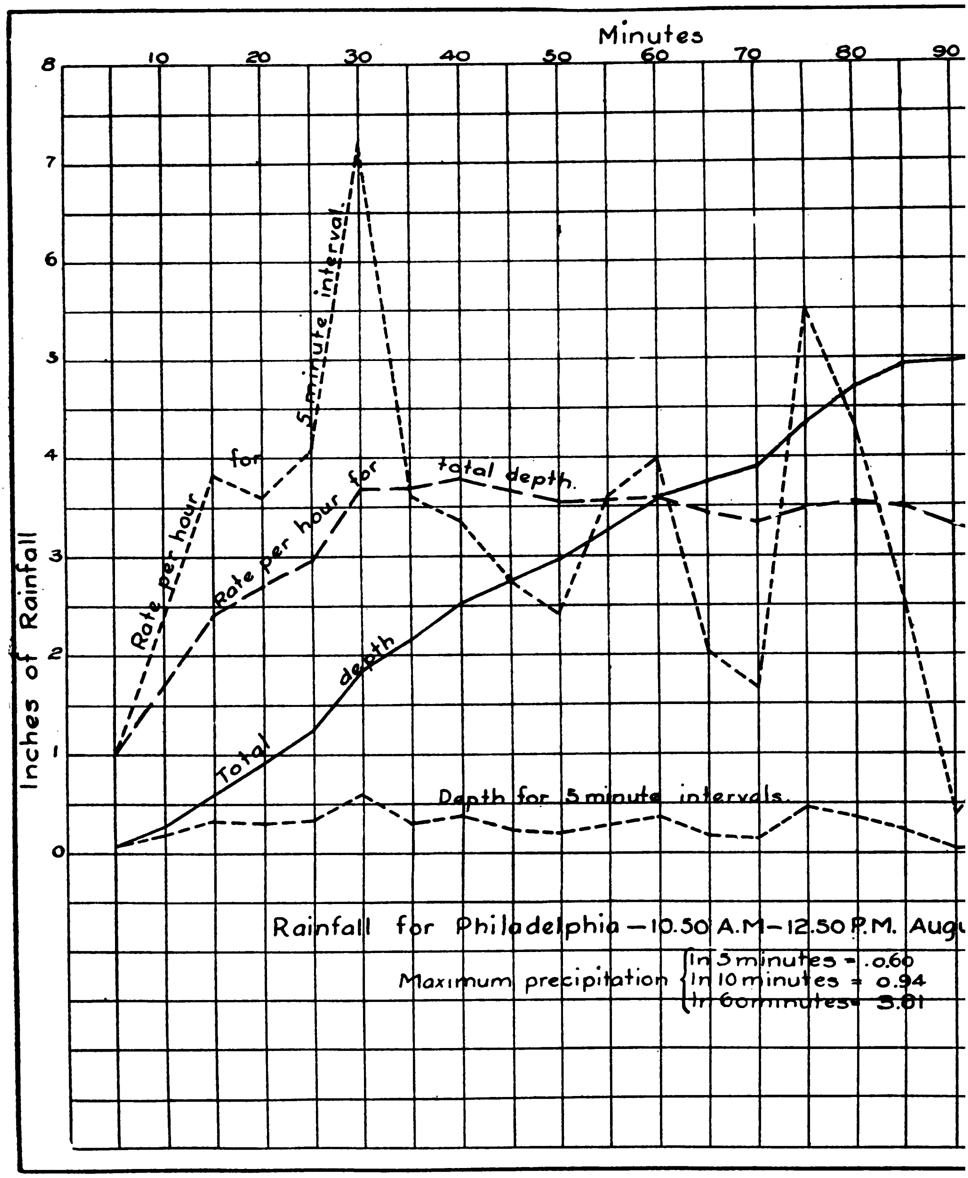
Rainfall at
Escanaba, Mich. July 21, 1903.
12.35 P.M. to 1.10 P.M.

Maximum Precipitation
In 5 minutes = 0.69
In 10 minutes = 1.32
In 15 minutes = 1.52

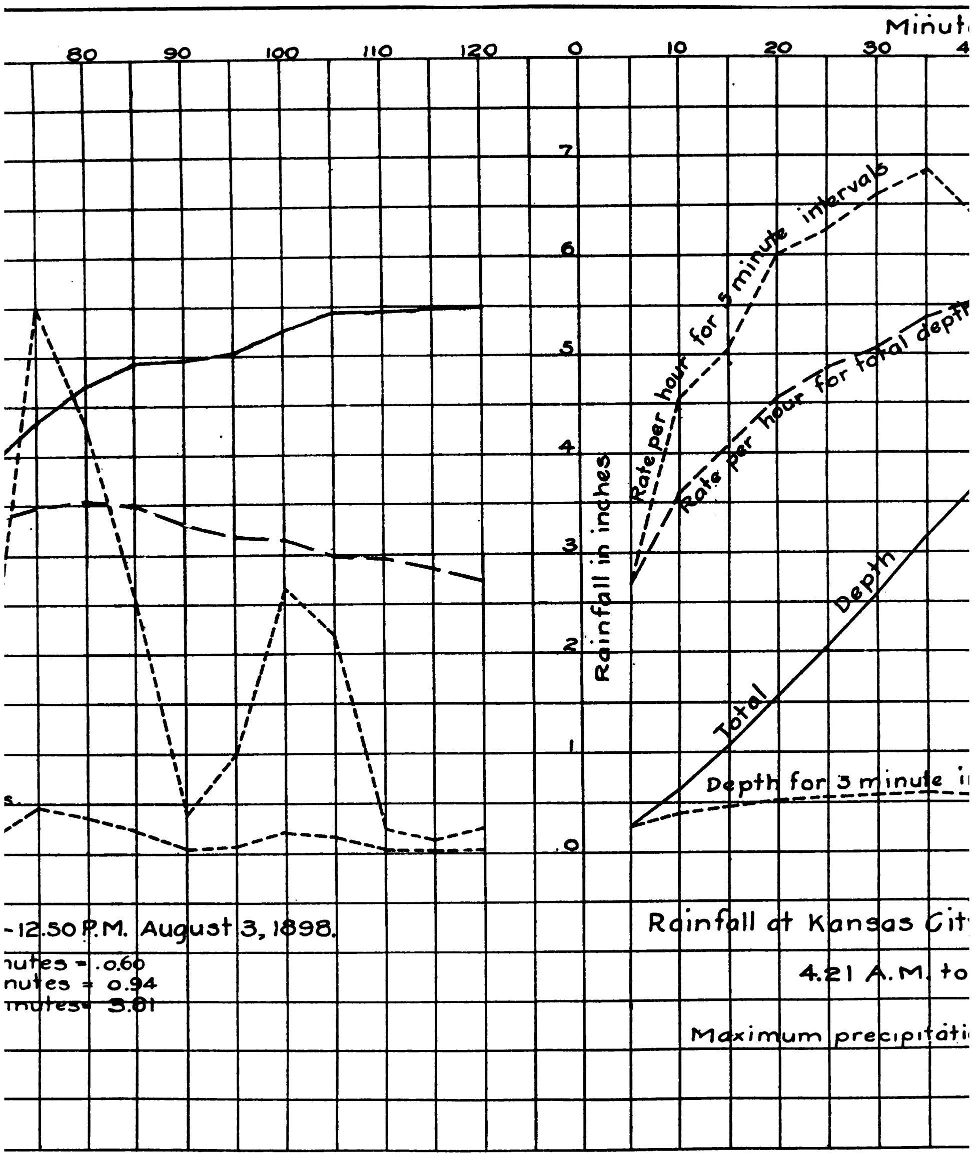
Rainfall at
Baltimore Md. July 12, 1903.

Maximum Precipitation
In 5 minutes = 0.80
In 10 minutes = 1.39
In 15 minutes = 1.92.

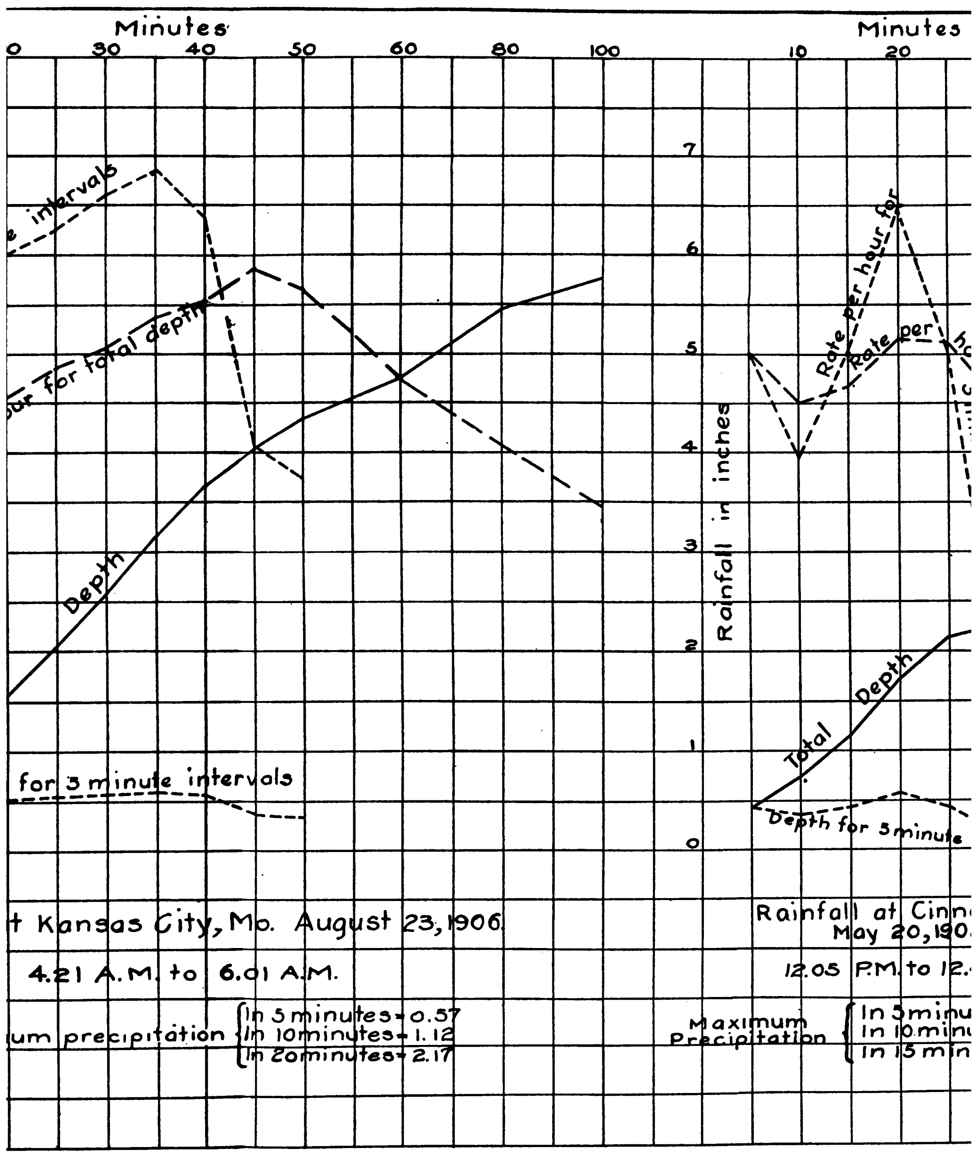
PLATE 12

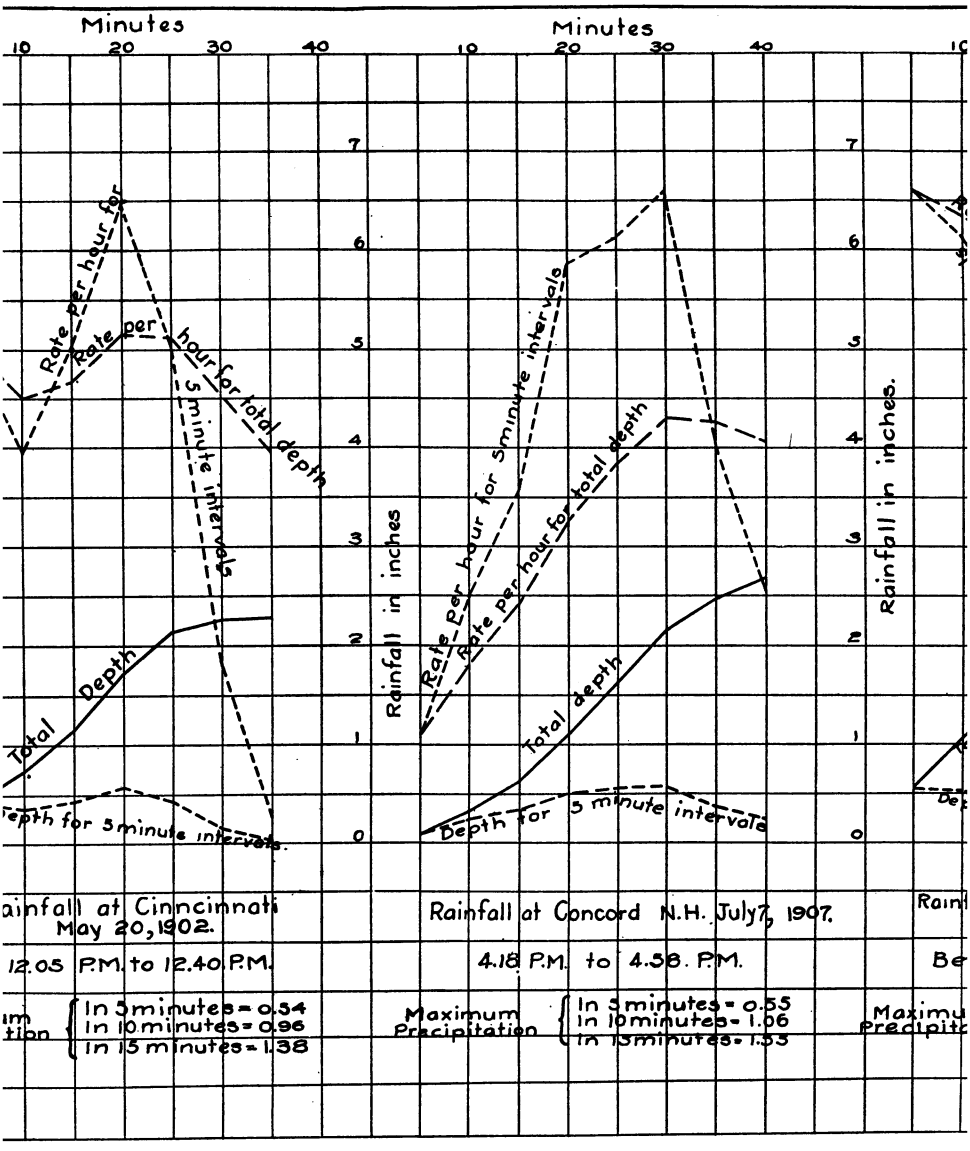


Minutes
10
20
30
40
50
60
70
80
90
8
7
6
5
4
3
2
1
0
Inches of Rainfall
Rate per hour for 5 minute interval.
Rate per hour for total depth.
Total depth
Depth for 5 minute intervals.
Rainfall for Philadelphia — 10.50 A.M — 12.50 P.M. Augu
Maximum precipitation
In 5 minutes = .0.60
In 10 minutes = 0.94
In 60 minutes = 3.01

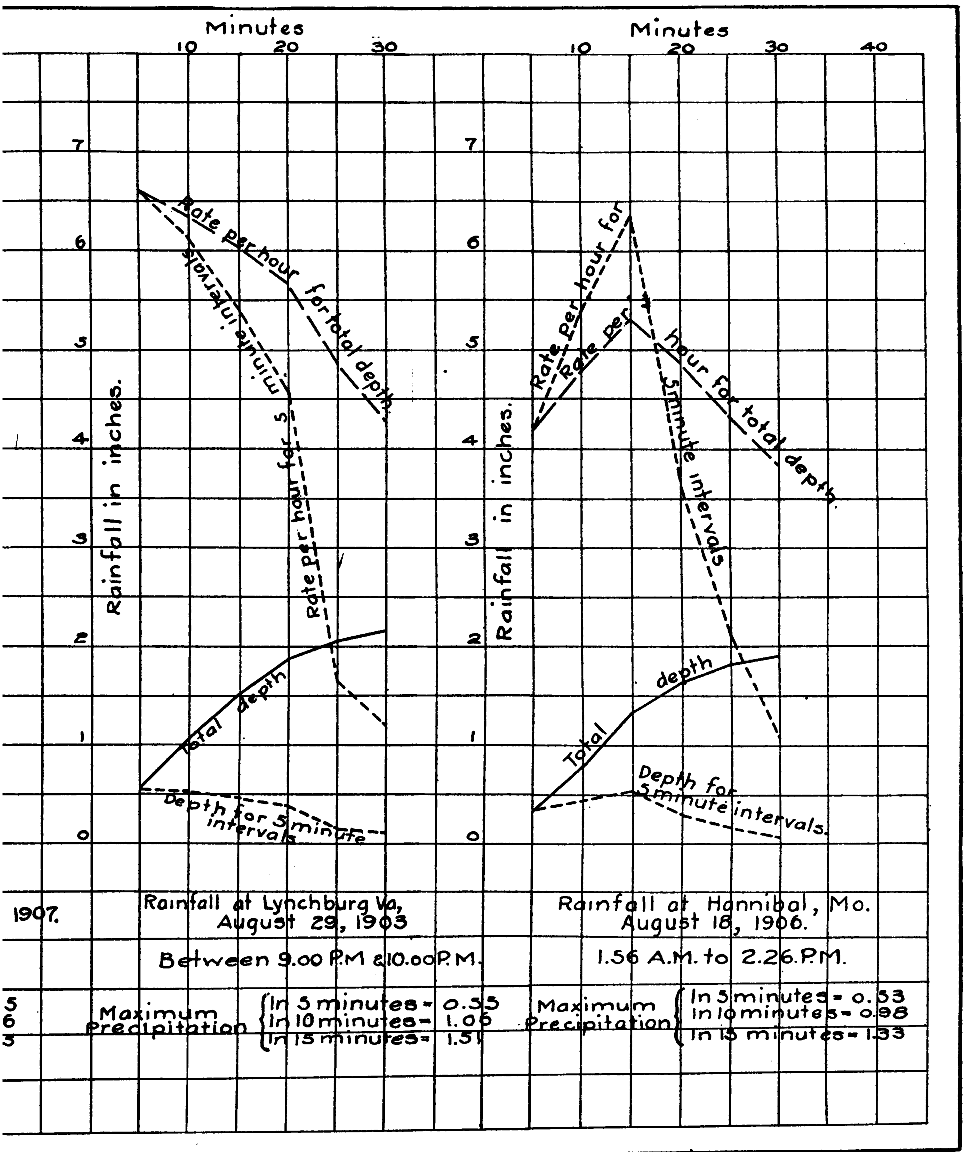


Minut
80
90
100
110
120
0
10
20
30
4
7
6
5
4
3
2
1
0
Rainfall in inches
Rate per hour for 5 minute intervals
Rate per hour for total depth
Total Depth
Depth for 5 minute i
-12.50 P.M. August 3, 1898.
nutes = .0.60
nutes = 0.94
nutes = 3.81
Rainfall at Kansas Cit
4.21 A.M. to
Maximum precipitati


Minutes
0 30 40 50 60 80 100
e intervals
our for total depth
Depth
for 3 minute intervals
t Kansas City, Mo. August 23, 1906
4.21 A.M. to 6.01 A.M.
um precipitation
In 5 minutes = 0.57
In 10 minutes = 1.12
In 20 minutes = 2.17
Rainfall in inches
0 1 2 3 4 5 6 7
Minutes
10 20
Rate per hour for
Rate per ho
Total Depth
Depth for 5 minute
Rainfall at Cinc
May 20, 190
12.05 P.M. to 12.
Maximum Precipitation
In 5 minu
In 10 minu
In 15 min



Minutes
10
20
30
40
Minutes
10
20
30
40
7
6
5
4
3
2
1
0
Rate per hour for
Rate per hour for total depth
5 minute intervals
Total Depth
Depth for 5 minute intervals.
Rainfall in inches
Rate per hour for 5 minute intervals
Rate per hour for total depth
Total depth
Depth for 5 minute intervals
Rainfall in inches.
ainfall at Cincinnati
May 20, 1902.
12.05 P.M. to 12.40 P.M.
In 5 minutes = 0.54
In 10 minutes = 0.96
In 15 minutes = 1.38
Rainfall at Concord N.H. July 7, 1907.
4.18 P.M. to 4.58. P.M.
Maximum
Precipitation
In 5 minutes = 0.55
In 10 minutes = 1.06
In 15 minutes = 1.53
Rain
Be
Maximu
Precipita



Minutes
10
20
30
Minutes
10
20
30
40
7
6
5
4
3
2
1
0
Rainfall in inches.
Rate per hour for total depth.
minute intervals
Rate per hour for 5
Total depth
Depth for 5 minute intervals
Rate per hour for
Rate per hour for total depth.
5 minute intervals
Total depth
Depth for 5 minute intervals.
1907.
Rainfall at Lynchburg Va,
August 29, 1903
Between 9.00 P.M & 10.00 P.M.
Maximum Precipitation
In 5 minutes = 0.55
In 10 minutes = 1.06
In 15 minutes = 1.51
Rainfall at Hannibal, Mo.
August 18, 1906.
1.56 A.M. to 2.26 P.M.
Maximum Precipitation
In 5 minutes = 0.53
In 10 minutes = 0.98
In 15 minutes = 1.33

PLATE 13

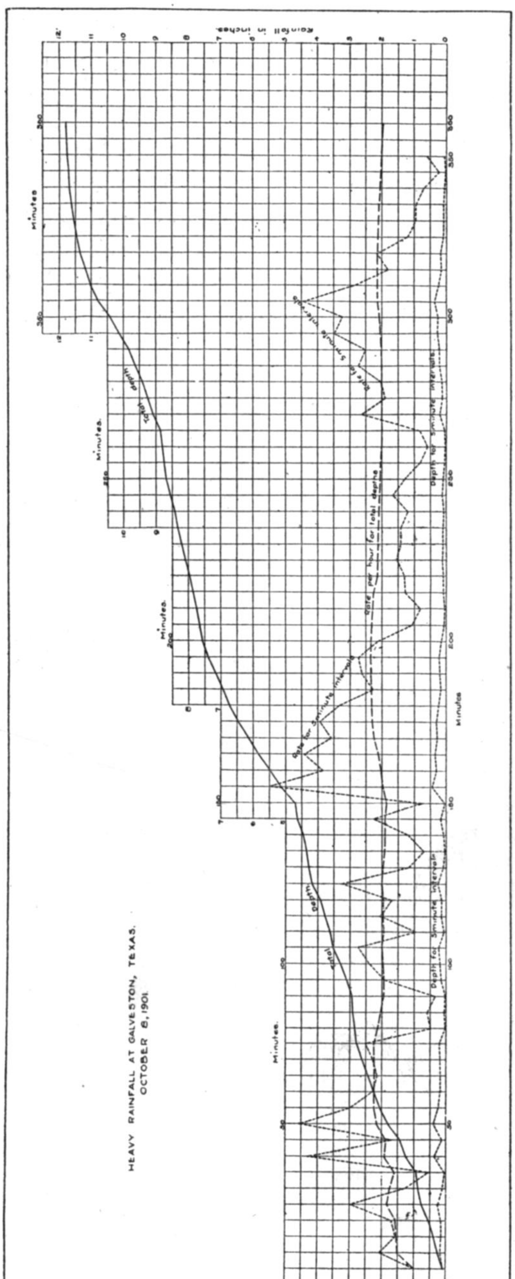

HEAVY RAINFALL AT GALVESTON, TEXAS.
OCTOBER 8, 1901.
Minutes.
Rainfall in inches.
Total depth
Rate for 5 minute intervals
Rate per hour for total depth
Depth for 5 minute intervals

PLATE 14

The character of the watershed is an important element in such runoff calculations, for it is not a mere theory to state that configuration and topographic features of a small watershed may produce higher runoffs from 2 inches in 40 minutes than the same amount in 30 minutes, but of course each case is individual. Protection or automatic provision is required to meet these, for such storms occur with little warning, and their rapid culmination offers no opportunity for opposing flood conditions as they approach. Not only is ample discharge capacity for reservoirs demanded, but pumping equipment adjoining streams must be located above lines of flood damage.

A 50 per cent runoff does not seem excessive for a severe storm, but this proportion from a downpour of 1½ inches in 30 minutes equals 968 second feet from each square mile, or 1½ second feet from every acre. (This is the estimated maximum runoff from Mill Creek watershed at Erie on August 3, 1915.) Civic engineering has given much attention to the disposal of the high runoff which results from intense storms falling on areas largely impervious.

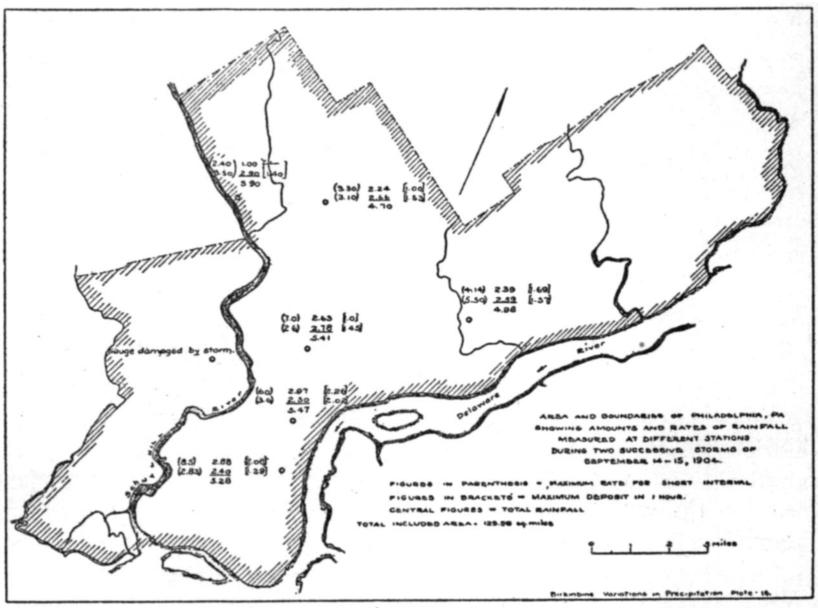
Irregular frequency of severe storms is illustrated by Kansas City, Missouri, which in September, 1914, received 16.17 inches of which 92 per cent fell in 4 storms, and 43.5 per cent in one rain. Rockport, Massachusetts, had 10.77 inches of rain in July, 1911. There were 7 days with rain, 2 of which supplied nearly 70 per cent of the total deposition.

An intense storm, on July 15, 1914, covered an area of 30 square miles in Pennsylvania, and produced severe flood conditions on a dozen small streams.

May 4 and 5, 1902, a cloudburst over a large area in Oklahoma caused destruction to life and property at Foss. The excessive rain continued 40 minutes, and much damage was done at Guthrie, which received 4 inches in the 2 days, whereas the normal total for May is 3 inches. On the 22nd Guthrie received 2.2 inches as its share of a severe rain which gave for the 21st and 22nd totals of 2.13 inches to 8.17 inches, the average 2 day total for the 12 stations equalling 4.55 inches. During this storm, between Fort Reno and Oklahoma City a rectangular trough, 10 inches deep and in an exposed location, was entirely filled and probably overflowed between night and morning.

At Philadelphia, Pennsylvania, in mid-September, 1904, 2 intense storms 7 hours apart, gave three-quarters of the total deposition for the month, and these severe downpours were felt over a large

area of the city. On plate 16 are shown the rainfalls recorded at 6 rain gauges in the city during these 2 storms, one being an official Weather Bureau Station and the others maintained by the Bureau of Surveys. Unfortunately another pluviometer was put out of commission by the first storm, so that the severity could not be determined, but it must have been unusual. The area within the city boundaries is nearly 130 square miles, and though the entire territory was not covered with gauges, the total quantities recorded for the 2 storms at the different stations, which ranged from 9,060,000 to 12,600,000 cubic feet per square mile, illustrate the vast quantity



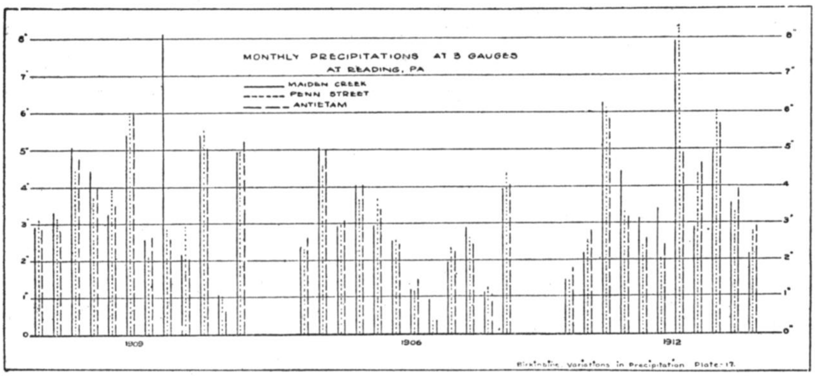
Birkinbine Variations in Precipitation Plate 16.

of water which fell. Other severe storms show similar variation in entire amounts and maximum short-time intensities, the differences between two of these stations in some instances being very extreme, a condition that would be expected of intense storms over such an extended area.

Even in small distances the inequality of rainfall received during such storms is material. Records of adjoining gauges show the major differences in the season of torrential rains, and the inequalities are frequently very large. The daily records of rainfalls given on plate 17 show that the extreme discordance of the totals for

August 1906, and July 1912, were due to such conditions.[2] Severe storms in close succession are frequent in the more southern humid regions. Studies of records of excessive precipitation for different locations illustrate the inconstancy of this feature, both in intensity and frequency.

Instances are given in Table 6.



THUNDERSTORMS

Precipitation from thunderstorms is experienced over a large portion of the country, the location of maximum frequency being in Florida, and the lower Mississippi Valley, and the least susceptible district, the Pacific and New England coasts. Localities near high mountains are subject to many such storms, often of unusual severity. In the arid regions thunderstorms occur, but generally the rain is evaporated in transit, little or no water reaching the earth, and "dry thunderstorms" are at times recorded at other localities.

The severe electrical storm of August 16, 1914, near Tonapah, Nevada, was without any precipitation. Santa Fé, New Mexico, had for the period 1904–1913 annual averages of 73 days with thunderstorms, 96 days with precipitation, and 14 inches of precipitation; and the year 1910 had 76 days with thunderstorms, 75 days with rain, and a total of 8.65 inches of water.

Professor Humphreys has shown that, being caused by rapid vertical convection of humid air, the genesis of thunderstorms is either by excessive insolation, or by a layer of air being overrun by

[2] These three gauges are separated by distances of 6.28, 6.12 and 2.82 miles.

TABLE 6

Records of some severe storms

LOCATION	DATE	DEPTH IN INCHES	DURATION Hrs.	DURATION Min.	AVERAGE RATE PER HOUR
Albany, N. Y.	July 10, 1876	1.12	0	10	6.72
Alpena, Mich.	September 20, 1884	1.05	0	11	5.73
Amanda, Ia.	July 31, 1878	1.56	0	15	6.24
Atlanta, Ga.	April 24, 1889	1.12	0	10	6.72
Atlanta, Ga.	July 23, 1898	4.30	0	51	5.06
Berne, Ind.	August 16, 1913	2.55	0	30	5.10
Biscayne, Fla.	March 28, 1874	4.10	0	30	8.20
Brandywine Hundred, Pa.	August 5, 1843	10.00	2	0	5 00
Cambridge, Ohio	July 16, 1914	7.09	1	30	4.73
Catskill, N. Y.	July 26, 1819	18.00	7	30	2.40
Chicago, Ill.	May 25, 1896	1.24	0	15	4.96
Collinsville, Ind.	May 23, 1888	1.70	0	12	8.50
Concord, Pa.	August 5, 1843	16.00	3	0	5.33
Embarrass, Wis.	May 28, 1881	2.30	0	15	9.20
Flatbush, L. I.	August 22, 1843	9.00	8	0	1.12
Ft. Leavenworth, Kan.	July 21, 1887	1.90	0	20	5.70
Ft. McPherson, Neb.	May 27, 1868	1.50	0	5	18.00
Ft. Randall, S. D.	May 28, 1873	1.56	0	15	6.24
Ft. Scott, Kan.	October 2, 1881	1.80	0	20	5.40
Galveston, Tex.	June 4, 1871	3.95	0	14	16.93
Huron, S. D.	July 26, 1885	1.30	0	10	7.80
Indianapolis, Ind.	July 12, 1876	2.40	0	25	5.76
Jewell, Md.	July 27, 1897	14.75	18	0	0.82
Lebanon, Pa.	July 10, 1914	5.00	2	0	2.50
Long Branch, N. J.	July 14, 1912	0.80	0	5	9.60
Newton, Pa.	August 5, 1843	5.50	0	40	8.25
Newton, Pa.	August 5, 1843	13.00	3	0	4.33
New York, N. Y.	May 22, 1881	1.15	0	10	6.90
New York, N. Y.	November 18, 1886	0.25	0	2	7.50
Osage, Ia.	August 26, 1881	1.40	0	15	5.60
Ottawa, Ohio	August 21, 1913	2.28	0	40	3.42
Palmetto, Nev.	August 7, 1890	8.80	1	0	8.80
Paterson, N. J.	July 13, 1880	1.50	0	8	11.25
Philadelphia, Pa.	September 12, 1862	9.00	5	0	1.80
Portsmouth, Ohio	June 22, 1851	1.75	0	15	7.00
Sandusky, Ohio	July 11, 1879	2.25	0	15	9.00
San Francisco, Cal.	December 20–21, 1866	7.76	8	45	0.89
St. Louis, Mo.	August 15, 1848	5.05	1	0	5.05
Stroudsburg, Pa.	August 1, 1913	7.50	3	50	1.96
Tridelphia, W. Va.	July 19, 1888	6.90	0	55	7.53
Washington, D. C.	July 26, 1885	0.96	0	6	9.60
Worthington, Minn.	August 20, 1913	8.00	11	0	0.73

a sufficiently colder strata, the cause of ocean thunderstorms and of some on land, or by a saturated body of air being underrun and lifted by a denser layer. Consequently, land thunderstorms are most frequent in the latter portion of the afternoon, while those on the oceans more often occur shortly after midnight. He also mentions five barometric conditions with whose occurrence thunderstorms are likely. These are (a) high temperatures of nearly uniform pressure over large areas, causing heat thunderstorms; (b) cyclonic storms; (c) a barometric valley enclosed in a "V" shaped cyclonic isobar, occurring in a region of tornadoes and often termed tornadic thunderstorms; (d) a trough of low pressure between two areas of high pressure, these he terms anticyclonic or trough thunderstorms, and (e) the boundary between warm and cold waves, designated as border thunderstorms.

Current opinion often holds that thunderstorms follow valleys, but notation of paths of such storms indicates that they are produced at too great a height to be affected by minor topography, though the predominance of moist air in watered valleys may contribute to their formation in such places.

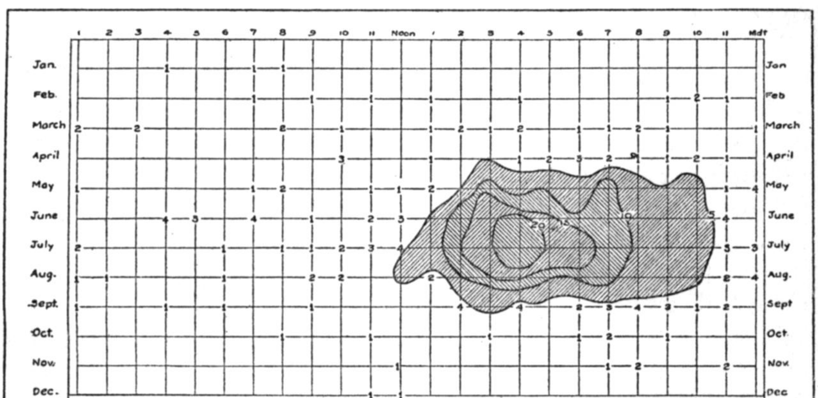
Reference to records indicates that winter thunderstorms are more common than is generally supposed, but as they lack the intensity and duration of the thunderstorms of summer and seldom bring hail, they frequently pass unnoticed, especially when occurring at night. They are credited to cold air over-running a stratum of relatively warm air, and are most common adjacent to the Atlantic and Gulf coasts with increasing frequency at lower latitudes.

Prof. Oliver L. Fassig's chart of hourly and seasonal occurrence of thunderstorms at Baltimore, Maryland, is reproduced by permission on plate 18, and clearly illustrates the predominance of heat thunderstorms at the time the earth's surface has become well warmed by continued insolation.

Messrs. Cox and Armington have pointed out that the predominance of May thunderstorms in Chicago at about 4 a.m. is due to the alternation of lake and land breezes, as the wind from the Lake reaches a maximum about this hour, at a season when the general temperature is rapidly increasing; while the maximum occurrence of ocean thunderstorms is in the early morning hours, when the difference between surface and air temperatures reaches a maximum and encourages rapid vertical convection.

As affecting the occurrence of rain the thunderstorm is in many

localities an important factor, for it may furnish the majority, or even all the rainfall during periods of deficient precipitation. Much of the summer rainfall of New Orleans occurs with thunderstorms, and other Gulf and South Atlantic regions have recorded in some years over 100 thunderstorms per annum, the majority in June, July and August, when two or more thunderstorms in one day are of frequent occurrence. The summer rainfall in the lower elevations of Arizona is almost entirely due to thunderstorms. Other localities, extending well to the north, receive most of their summer rain by thunderstorms. While many thunderstorms are local, meteorological conditions may produce large areas of thunderstorms, as in Missouri and southern Illinois, May 25 and 26, 1893.

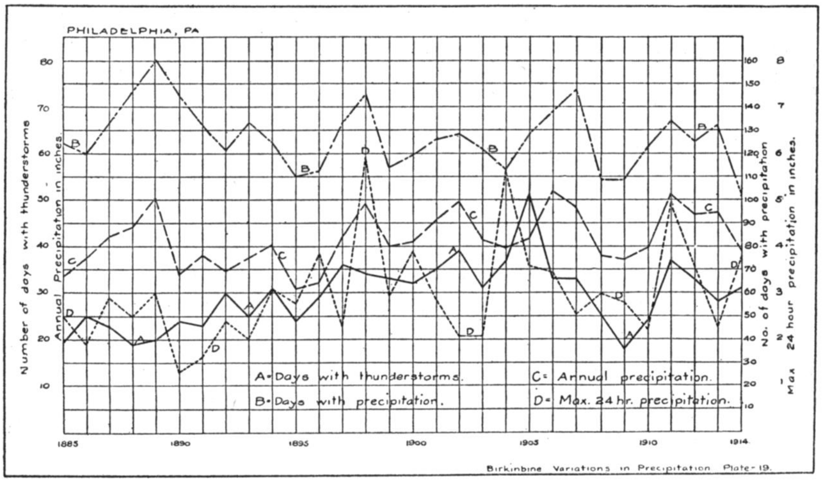


THE FREQUENCY AND DISTRIBUTION OF THUNDERSTORMS AT BALTIMORE MD. 1871-1900 ACCORDING TO O.L. FASSIG.

Birkinbine Variations in Precipitation Plate 18.

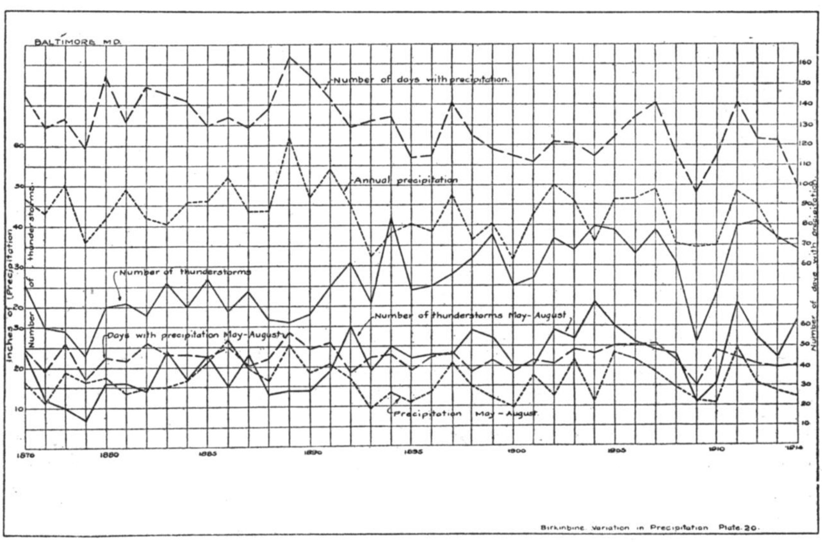
Plates 19, 20 and 21 indicate for several localities how the frequency of thunderstorms and the total quantity of water deposited follow a similar trend in the majority of years, while the years of disagreement illustrate in a general way the relative effect of thunderstorms with heavy downpours, as well as those of slight or no rain. These variations are illustrated in plate 22, plotted from Mr. J. H. Spencer's tabulation of data for Lincoln, Nebraska.

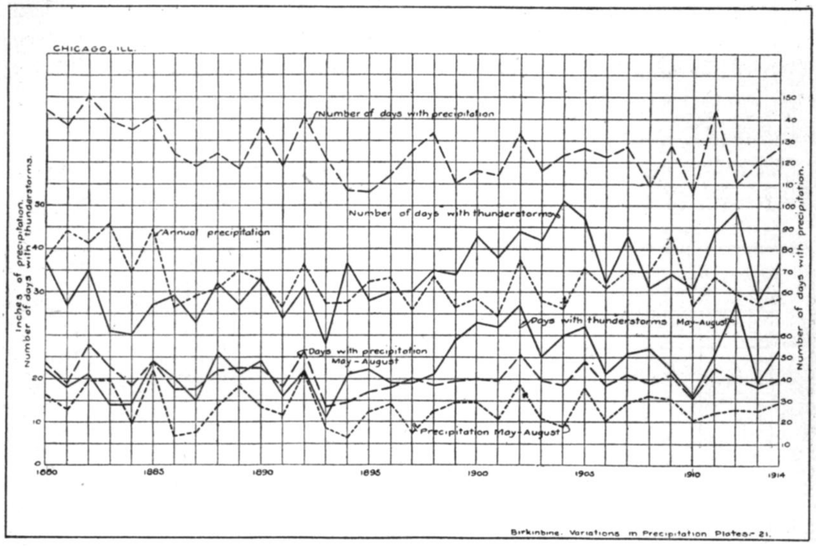
A relation between warm temperatures and frequency of thunderstorms can be expected, especially in humid regions. A more marked tendency to synchronism is illustrated by the curves for the period of major occurrence of thunderstorms on the lower field of plates 20 and 21. The Baltimore record is of the number of thunderstorms, the others of number of days with thunderstorms.



It should be noted that the thunderstorm records maintained by the Weather Bureau properly note all thunderstorms, whether or not any rain occurs, though formerly only thunder with rain was recorded.

As with many other precipitation records, the exceptions are lost in the average of a large number of records, as shown on plate 23, after a diagram accompanying Professor Humphreys' article on

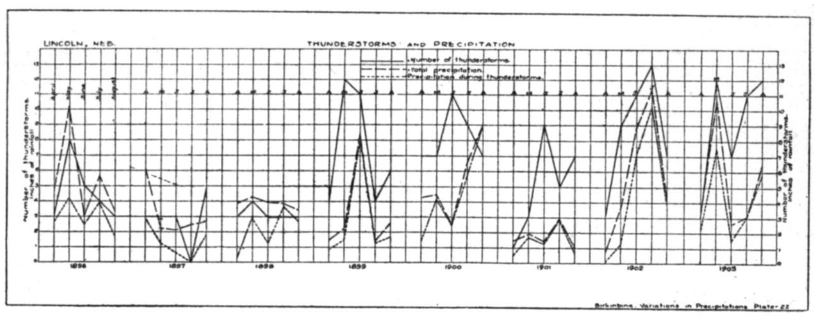




"The Thunderstorm and its Phenomena," and in which he states that the relation is substantially similar for the areas east and west of the 100th meridian, though the climates of these two districts are so radically dissimilar.

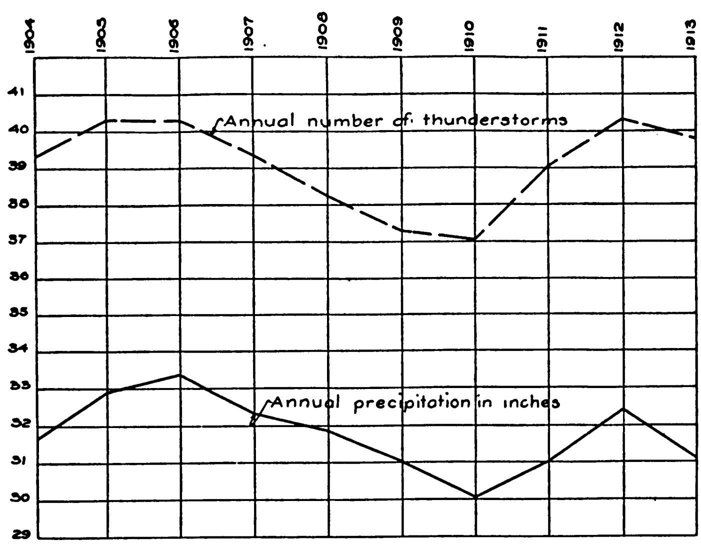
Prof. Humphreys used records subsequent to 1904 only, so as to have data on a uniform and reliable basis, for he was unable to justify the remarkable increase in records of thunderstorms between 1890 and 1904, although he referred to a keener observance of meteorological phenomena in later years.

Some investigators have noted a tendency to periodic cycles in the occurrence of thunderstorms, which may be traced on the various diagrams of occurrence, and which is suggested by records



of thunderstorms at other locations. Being due to meteorological causes it is expected that this feature would vary in a general way with other conditions, and be most frequent in warm periods, and the cycles accordingly display nonuniformity in occurrence and magnitude.

As affecting water supply the thunderstorm is less satisfactory, by reason of the severity with which the water falls, causing high



RELATION BETWEEN NUMBER OF THUNDERSTORMS.
AND ANNUAL PRECIPITATION
AVERAGED FOR 127 WIDELY SCATTERED
STATIONS IN THE UNITED STATES

Birkinbine.- Variations in Precipitation. Plate-23.

runoff and little percolation, increased erosion and turbidity, and possibility of damage not only to structures but to existing water mains in soil subject to saturation from overflowing stream channels or storm sewers. The remarkable rainfall of August 3, 1898, at Philadelphia, see plate 13, occurred during the most severe electrical storm recorded there, and all the severe rains noted on plates 11 to 13 occurred during thunderstorms.

Many other torrential rains take place during thunderstorms, and such are marked by more pronounced irregularity of rate of deposition and unusual intensity during some of the brief intervals. However, the quantity of precipitation is not to be measured by the violence of the hail or wind, especially in tornadic thunderstorms, for the thunderstorm squalls have furnished many of the destructive winds. Many have noted the more intense rain which we observe after a lightning flash, although it is the excessive condensation of rain in the storm cloud which creates the electric discharge; and Mr. William A. Bentley's investigation of rain drops showed large drops to be more frequent during the occurrence of electrical storms. These last two features tend to compact the earth, for the velocity of falling rain drops may reach 25 feet per second, and consequently the direct runoff is increased.

FROZEN PRECIPITATION

Hail, which is an adjunct of thunderstorms, has fallen in excess quantities at a number of locations, depths of more than a foot having been noted in the Middle and North Atlantic region. Because of the high water content, its occurrence in the early stages of a thunderstorm, the probable immediate sequence of torrential rains, and the warm temperature of the season, unusual deposition of hail may cause a high runoff. In such cases the quantity is of more import than the size of individual hail-stones or agglomeration of these into large lumps. Fragile apparatus is to be protected against hail, and where electrical equipment is in service the layout should be such that windows broken by hail will not allow the subsequent hard wind-driven rain access to electrical apparatus that would suffer damage or be eliminated from service by water.

Sleet, frozen raindrops, or rain freezing as it falls, ice storms, which sometimes occur in intermittent succession so that they are practically in combination, tend to form an impervious coating on the soil or on snow, and these permit quick runoff from subsequent rain. Ice storms, by the heavy coating deposited on trees and wires, have frequently interrupted electrical service, and there are instances of the supporting poles or towers being broken or pulled awry. Automatic flashboards, exposed operating devices for gates, etc., are seriously hampered by such an ice covering.

Plate 24 reproduces an instance of damage from an ice storm over a moderate area. The effect is illustrated by the fact that a small

twig carried 27 times its weight of ice. A study of 211 storms showed a sleet thickness of less than $\frac{1}{4}$ inch for 42.6 per cent; from $\frac{1}{4}$ to $\frac{1}{2}$ inch for 29.4 per cent; from $\frac{1}{2}$ inch to 1 inch for 19.9 per cent and more than 1 inch for 8.1 per cent.

The destruction by a combination of snow, rain and ice storms affected about 600 square miles, and measurements showed branches $\frac{1}{4}$ inch thick entirely surrounded with a thickness of 1 to $1\frac{1}{2}$ inch. At Phillipsburg, New Jersey, this storm extended through 98

hours, and the range of temperature in this entire interval was but 6°F., and there was little wind to aggravate conditions.

Temperature conditions of the different air strata are an important factor in precipitation rates, for many hail-stones are melted into raindrops, or even evaporated before reaching the earth; while condensed moisture is frequently frozen in transit.

The sleet and ice storms of the Upper Ohio region in March 1912, covered an area 75 miles wide and 450 miles long, and those in Eastern Pennsylvania, in 1914, were marked in some localities by a narrow path and by spots of severity.

SNOW

Snow usually steadies the runoff as the melting deposit feeds the ground, especially when, as occasionally occurs, the snow blanket falls before the ground freezes.

Freshly fallen snow contains from 3 per cent to 14 per cent of water, as it varies from the dry feathery type to that of a soft wet character, and much of the falling snow can be included in the range of from 8 per cent to 12 per cent of water. But snow on the ground acquires a higher moisture content, due to compaction by weight of the upper portions, absorption of heat radiated from the earth, melting of the upper layers by sun and by mild temperature, and by absorption of moisture from humid air. Actual tests have shown laid snows to have water equivalent from 20 per cent to 60 per cent and it is the actual water content rather than the depth of snow which is important.

In the warmer regions of rare snow its occurrence in quantity is likely to have an appreciable effect on water supply, for the snow deposited is in such cases quickly melted and may create high runoff conditions. Some snow has been reported over nearly all the United States, but slight flurries, or even several inches depth, do not contain sufficient water to seriously affect runoff.

Snow in considerable quantity is reported to have fallen at Charleston, Savannah, Mobile and Pensacola in 1866; other southern instances being, 4 inches at New Orleans (1852), 5 inches at Montgomery, Alabama, December 29–31, 1880, and on the same date nearly 2 inches at Rio City, Texas; while Memphis, Tennessee, received 18 inches of snow on March 16 and 17, 1892. Mr. C. F. Volney mentioned a 5-foot snowfall at Norfolk on February 4, 1798.

Over much of the areas which experience some snow each winter the occurrence, distribution and the amount show a greater range than rainfall records, for temperature conditions determine the character of precipitation. In 1914 the total precipitation at Columbus, Ohio, was four-fifths the normal, but the snowfall was 50 per cent above mean, while Indianapolis, Indiana, had a total precipitation that was three-fourths the normal, and the second lowest yearly record, but the snowfall was nearly twice the average and the second highest annual.

The Christmas snowstorm of 1909 was described as the most severe over a large area in a half-century. Nearly all sections

from the Missouri River to the Atlantic Ocean, except New England where the snow fell on the 26th, received rain or snow on the 25th, the southern boundary of snow passing through Wilmington, North Carolina, and Augusta, Georgia, thence south of Birmingham, Alabama, and Vicksburg, Mississippi, and north of New Orleans and Galveston. The maximum deposits occurred in Pennsylvania and Delaware, where the average depth was 20 inches.

On January 10 and 11, 1905, 6 inches to 30 inches of snow occurred in 15 states, and on April 3, 1915, a snow storm extending along the Middle Atlantic Coast gave an average of 19 inches, an April record, at Philadelphia, Pennsylvania. Mr. Charles Pierce noted a 3-foot snowfall for this locality on April 19, 1741, but verification of the accuracy of this record is lacking.

Springfield, Missouri, in the winter of 1911–1912 had 53.1 inches of snow, the 20 inches which fell on February 20, 1912, exceeding any previous monthly record for 25 years, and being greater than most annual totals. At Grantville, Maryland, the snow from October, 1910, to the following April inclusive, totalled over 100 inches, and Blue Knob, Pennsylvania, had 96 inches of snow in December, 1890.

Mountain regions with their heavier precipitation, where exposed to humid winds, receive larger quantities of snow, which owing to the cooler temperature, and often on account of shading by forests, melt slowly. The west and northwest offer examples of a summer supply of water from slowly melting mountain snow, and northern locations in other regions illustrate a generally non-excessive and well sustained spring runoff, due to the tardy melting of snow in well wooded districts. While the large catchment surface of trees holds much snow from reaching the ground and exposes this snow to the sun and air, these same branches shelter the forest floor.

Where part or all of the drainage area of a water supply lies in mountain land, consideration must be given to the deeper snows on the higher elevations. Moist clouds passing over a valley or moving up a slope may not be precipitated until the higher elevations are reached. But a distinct snow line, or a demarcation between snow deposits of materially different depth, is not always confined to the higher mountains. On a mountain drainage area in Lycoming County, Pennsylvania, the higher topography was but 500 feet above the valley plane, but the line of ice storm and deeper snow, 3 to 4 feet against but 15 inches to 18 inches a short distance below, was plainly marked along this and the neighboring hills.

An interesting case of snowfall distribution exists in New York State and is shown on plate 27, which gives variations in annual quantity and apportionment, and the relation between annual snowfall and precipitation. In February 1911 two localities in this State recorded 47 inches and 55 inches of snow, and at the latter place 48 inches fell the following month, while the snowfall at Adams, November 1900, to April 1901, totalled 334.5 inches, of which 96 inches was accounted for in February.

Especially unfavorable is that type of snow called a "blizzard," for though the actual depth of snow is often moderate, damages or inconveniences are caused by the high drifts formed.

The Chicago records indicate no fixed relation between the quantity of snow and the *mean* winter temperature. While the maximum seasonal snowfall since 1884 occurred in the coldest winter, a nearly equal quantity was measured when the mean temperature was above normal, and though the minimum recorded depth fell in a severe winter small amounts have been noted in warm winters.

Mr. C. F. Brooks gives to February the average maximum monthly snowfall on the Atlantic Coast, and the same month which is the coldest, in the Ohio Valley; but for the upper Mississippi Valley the maxima are in December and March.

Mr. Chas. A. Mixer, C.E., took a sample of snow on the ground, which was 38 inches deep and contained 27.6 per cent of water while 10 days later the depth was but 20 inches and the water content 49.2 per cent.

Mr. H. S. Cole measured drifts in Nevada at 9000 feet elevation, and obtained a sample 14½ feet deep with 46 per cent of water, and one of 13½ feet containing 38.4 per cent.

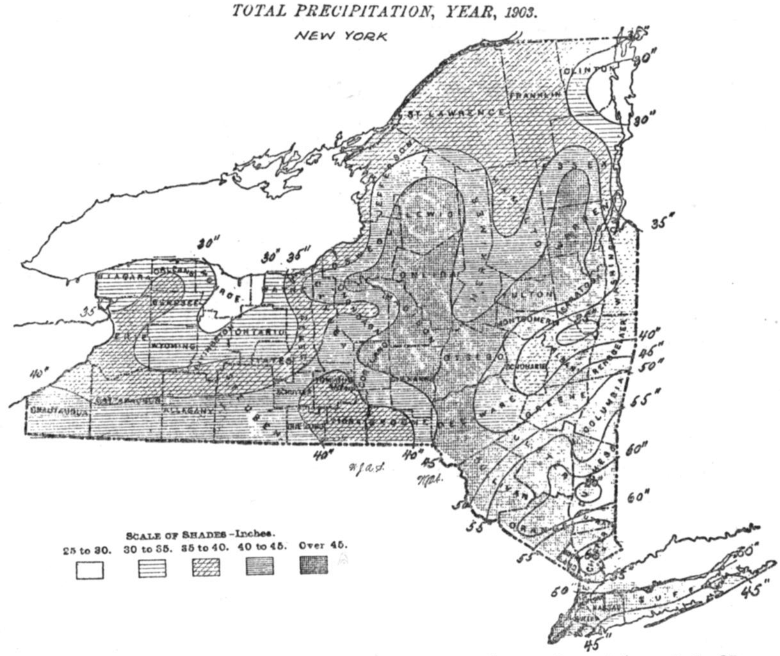
The measurements of Messrs. Thiessen and Alter of snow on the ground in the mountains of Utah, include the following average results:

Maple Creek Canon, average depth of samples, from 23 inches to 52 inches; per cent of water, from 22 to 35. In one case on a steep slope 24 per cent.

1911, average depth	35 inches, 31 per cent water
1912, average depth	42 inches, 24 per cent water
1913, average depth	48 inches, 25 per cent water

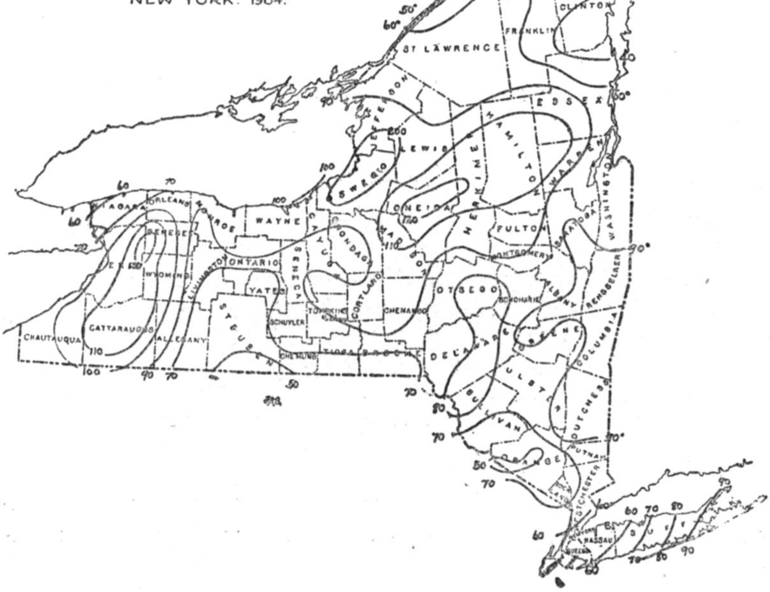
Measurements in Big Cottonwood Canon of snow at various locations, and thicknesses ranging up to 9 feet, showed a water equiva-

TOTAL PRECIPITATION, YEAR, 1903.



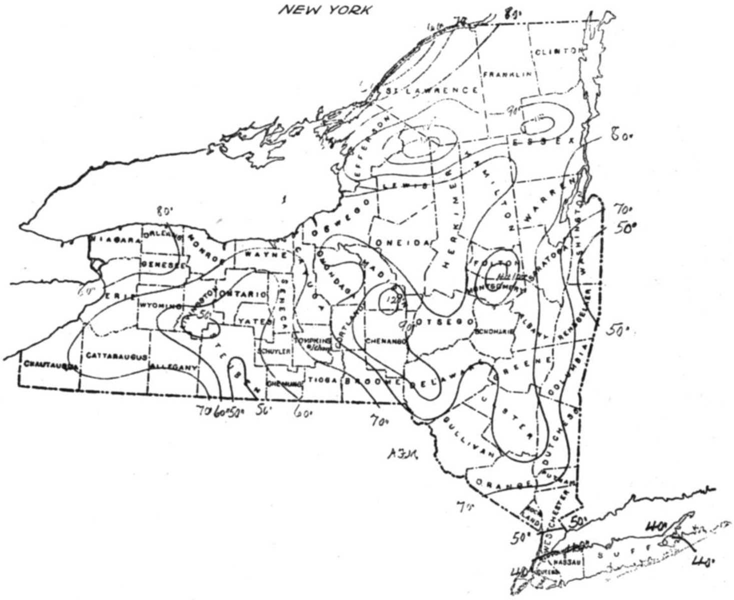
Birkinbine Variations in Precipitation. Plate 27

UNMELTED SNOWFALL IN INCHES
NEW YORK. 1904.



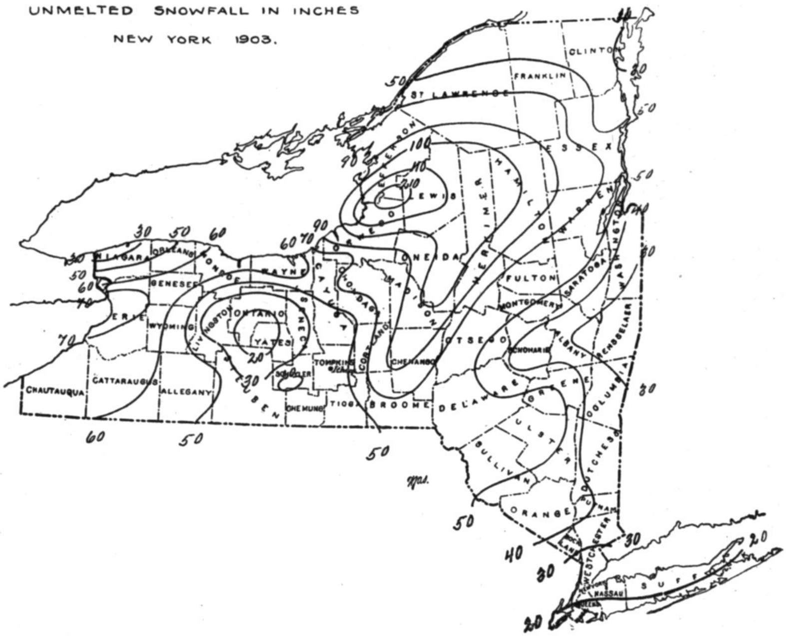
UNMELTED SNOWFALL IN INCHES, 1902.

NEW YORK



UNMELTED SNOWFALL IN INCHES

NEW YORK 1903.



lent ranging from 33 per cent to as high as 48 per cent, and one measurement $11\frac{1}{2}$ feet deep in a snow slide gave 56 per cent. The water equivalent for the entire watershed of 48.5 square miles was 21.5 inches in 1912, and 12.26 inches in 1913.

Slides not only bring down suddenly large quantities of snow, but also much debris to fill and clog any basin or watercourse below. The destructive action of large slides is illustrated by plate 28.

Mr. Alter states that snow lying late in the mountains becomes almost ice, and carries from 50 per cent to 75 per cent and even as high as 85 per cent water. Other measurements have shown snow on the ground carrying from one-fifth to one-third water, the quantity being less in shaded localities.

Mr. B. F. Eliason's measurements on the Pole Creek watershed in Utah, in April 1913, gave averages of 27 per cent to 32 per cent of water for depths ranging between 18 inches and 33 inches. Mr. R. R. Briggs, in March 1913, found an average content of 33 per cent for 15 inches to 20 inches on the high plateaus between the Salt and Little Colorado watersheds in Arizona.

Mr. A. C. McAdie has compiled interesting data concerning the snowfall at Summit, California, elevation 7017 feet, where 86 per cent of the precipitation occurs as snow, and the rainfall is mainly from July to September. These showed in 42 years a total seasonal precipitation varying from 80.1 inches to 21.8 inches of water, maximum monthly 30.40 inches in April 1880, and February 1904; and snowfall, 34 years' record, 783 inches to 153.5 inches, average 443.5 inches, with 298 inches for April 1880. Minimum monthly snowfalls recorded were January 1 inch, April 0.4 inch, December 0.2 inch, and for the other months zero. This location receives the greatest seasonal snowfall recorded in the states. Mr. A. H. Palmer gives the average annual totals as 420 inches of snow and 48 inches of precipitation.

A test of the water content of laid snow at different depths at Summit, gave,

At the surface	34 per cent
At 64 inches depth	45 per cent
At 174 inches depth	59 per cent

Where winters are severe a deep accumulation of snow is often formed after water surfaces are frozen over, giving large quantities of moisture to augment the direct runoff and rainfall when this occurs, and creating a brief but heavy discharge.

On small drainage areas which permit quick concentration of runoff, snows on ice or on frozen ground and melted by warm rains, have produced many extreme floods though of brief duration. The Port Neuf and Blackfoot Rivers in Southeastern Idaho were in flood in January, 1911, when heavy rain and warmth melted new snows lying on former deposits, which previous rain and cold had covered with ice, giving quick runoff.

The majority of floods from melting snow in the warmer regions have been on streams whose head-waters lie in mountain ranges; and recorded floods due to melting snow alone, or combined with rainfall, are more frequent in regions with annual occurrences of material snowfall, because of the larger quantities of the frozen moisture. Melting snow alone produced a severe and damaging flood at Barre and Montpelier, Vermont, in April, 1912. An average on the watershed of one-third inch of rain, with snow melted by warm air, occasioned the severe flood on the Grand River, Michigan, in the spring of 1904, and a similar condition brought about high water on the Mohawk River in the same season. But in less moderate regions, or similarly, when occurring in or just previous to mild weather at other localities, the rapid melting brings a quick runoff, often severely intensified by rain.

Mr. Mixer prepared some interesting charts of the relation between snow and rain on the watershed, and stream flow at Rumford Falls, Maine, which clearly illustrates the effects of a moderate warm rain and melting snow in increasing the river discharge, in April 1901, and the absence of the usual spring freshet the following year, because the ground was bare when the hard rains occurred.

The March 1907, flood at Pittsburgh, Pennsylvania, was due to a rainfall of about 2 inches in 2 days, and warm temperatures following snowfall on the Youghiogheny and Kiskiminitas watersheds; and the 1884 flood, caused by a winter thaw and moderate rains, furnished a greater total discharge in the Ohio River here than the notable inundation in the spring of 1913.

Standard building design allows for the weight of snow on roofs. Accepted practice protects electrical wires for operating motors, lights, etc., from short circuit, though where deep drifts are likely the wires must be sufficiently elevated to avoid grounding.

Unless melted by rain or temperature and then frozen, average snowfall will not hinder operation of exposed mechanisms, though it may affect accessibility to these.

DROUGHT PERIODS

The hydraulic engineer must measure intervals of deficient precipitation by records of occurrence and quantity, rather than by their effect on vegetation, especially as to the harvesting of crops which fail if requisite moisture is not absorbed at certain critical stages.

Reservoirs, streams and sub-surface waters, largely dependent on melted snow, will materially respond to deficiency of this deposit; storage basins relying on spring or autumn rains for replenishment become seriously depleted by unseasonable droughts, and high run-off from an intense storm falling on sun-baked soil results in a catchment exceeding the benefit to agriculture.

A succession of years of deficient precipitation exhibits the effects in reduced underground water storage. The late Dr. W. J. McGee stated:

Normal streams, being derived chiefly from seepage, are maintained directly by the store of water accumulated in the ground as the residuum of rains of preceding seasons and decades, and only indirectly by current rainfall. In the humid part of this country the ground water within the first hundred feet from the surface has been estimated at some 25 per cent of the volume of subsoil and rock, equivalent to 6 or 7 years' rainfall, i.e., it may be conceived as a reservoir of water 25 feet deep, coinciding in area with the humid region.

Where ground waters are the direct source of supply a period of deficient precipitation will exhibit the effect, and in some areas levels of ground waters are due to rainfall conditions at a distant locality. With lowered ground water levels changes in the character of the water supply are to be sought for. Smaller subsoil basins also become depleted by successive years of subnormal precipitation, one illustration of this being given in the records of some Pennsylvania streams fed by limestone springs. In 1910, the third successive year of deficient rainfall, these reached lower stages than in 1908, which experienced the most severe drought of the three years. As a contrast, many other streams supplied more largely by direct runoff showed minimum records in 1908.

The deficiencies of precipitation follow no known laws of extent or occurrence. The drought condition of July and September 1881 covered most of the territory east of the Mississippi River. March 1910 was dry and unusually warm over most of the United States, and the year was generally dry, especially in a large area in 7 contiguous states. The lack of rainfall affected many large areas in 1894 and 1895, the first being intensified by the low rainfalls of 1893. Some of the regional deficiences for 1894 and 1895, respectively, were:

Ohio Valley and Tennessee	11	and	11	inches
Upper Mississippi	12	and	7.8	inches
East Gulf	9	and	8.6	inches
New England	8.1	and	5.3	inches

Drought conditions in Pennsylvania occurred in 1876, 1881, 1887, 1895, 1900, 1904, 1908, with 1909 and 1910 also with pronounced deficiency, and in 1914. The recent succession of years with subnormal precipitation in much of New England and part of New York State has been widely noted.

In the period October 1910 to July 1911 the Arkansas River at Little Rock, draining 148,241 square miles, gave record low water stages since 1879, for each month of the interval. The summer and autumn of 1870 and the winter following, at Baltimore, Maryland, were each lacking in precipitation, the total deficiency being 15.18 inches. From November 1910 to May 1911, 6 Weather Bureau stations in Georgia and the Carolinas had from one-third to one-half of the normal precipitation for the period. The lowest proportion was at Charleston, S. C., which received but 23.06 inches. Old records credit this city for the interval October 1757 to April 1758, with but 4.95 inches of rain.

The 1903 drought in Kansas, the most severe in 60 years, which afforded for 3 months a total average rainfall for the state of 37½ per cent of the average, was the fourth consecutive year of deficient precipitation for that region, and the same summer, especially the month of August, produced droughts in 5 neighboring states.

Atlanta, Georgia, records deficient intervals as given in Table 7.

TABLE 7

Some drought periods at Atlanta, Ga.

INTERVALS	DAYS DURATION	PRECIPITATION DURING DROUGHT	
		No. days	Total amount, inches
August 10–October 21, 1884	73	9	0.28
September 13–November 11, 1886	60	7	0.42
September 14–November 9, 1891	57	6	0.18
August 31–October 10, 1897	41	2	0.14
September 5–November 1, 1904	58	1	0.10

From July 1910 to June 1911 the quantity noted was but 43 per cent of the normal.

Prof. A. J. Henry some years ago made an exhaustive investigation of droughts, considering as such intervals of three weeks or more when the total precipitation was 30 per cent less than normal. From more than 1000 of such periods at 20 selected stations east of

the Rocky Mountains, he listed the averages of the precipitation in the two weeks preceding, and that during the drought, and the proportions of each to the normal. The range in values was as follows:

Number of droughts per year	22–46
Per cent of precipitation in previous two weeks to normal for the period	144–218
Average days duration of drought	29– 47
Per cent of precipitation in drought to normal in that period	17– 24

Of these he wrote:

> Drought periods are preceded, in the majority of cases, by a single heavy rain or by several days of light to moderate rains. . . . . This appears to be true of both the semiarid regions of the west and the more humid regions of the east and south. . . . The depth of rainfall in the two weeks preceding droughty periods—that is whether 200 or 400 per cent of the normal, does not appear to bear any relation to the length or intensity of the drought.

That subsequent data and studies have caused no modification in his deduction attests the soundness of his conclusions.

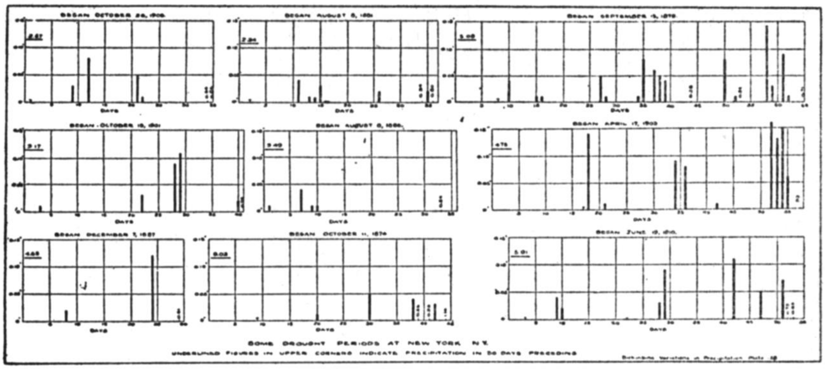
It is evident that some kind of a balance must exist, for deficiencies in precipitation can only occur when the causative conditions are reduced; likewise that the accumulated absorption of moisture by warm air is eventually subject to some condensation.

The meagre rainfall of Charleston, South Carolina, for the 6 months beginning November 1910, was succeeded by a 3 months interval, with 126 per cent of the normal precipitation. The excessive rains of September 1914, at Kansas City, Missouri, followed 2 droughts, from early April to mid-June, and again from early July to late August.

Mr. D. C. Reed's recent compilation of droughts in New York City lists the precipitation in the previous 30 days, and shows the subsequent rainfall records. Some of these are given in plate 29 and others in Table 8.

Similar data for droughts in Philadelphia, Pennsylvania, are offered on plate 30 and in Table 9.

Also beginning with July 23, 1895, 1.90 inches in 81 days; and in the 85 days subsequent to August 22, 1914, 2.85 inches. This last was followed by an unusual excess, the succeeding 72 days having a total of 16.06 inches of rain.

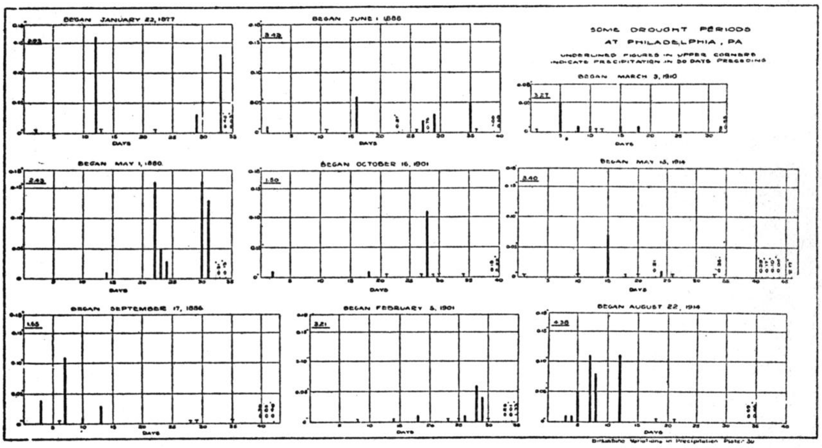


Boston, Massachusetts, subsequent to May 13, 1914, experienced 21 consecutive days of no measurable rain, then 0.10 inch in 1 day, and 10 successive dry days. This drought was preceded by 4.03

TABLE 8

Some drought periods at New York, N. Y.

BEGAN	PRECIPITATION IN PREVIOUS 30 DAYS	TOTAL PRECIPITATION IN		SUBSEQUENT PRECIPITATION IN		MAXIMUM CONSECUTIVE DAYS WITH LESS THAN 0.01
		Days	Inches	Days	Inches	
February 15, 1872	1.97	24	0	1	1.58	24
August 26, 1874	3.01	21	T	1	0.96	21
September 1, 1884	8.56	28	T	1	0.11	28
		31	0.15	1	0.28	
		41	0.32	1	0.11	
		51	0.43	1	0.80	
September 24, 1886	1.98	32	0.02	1	0.28	20
				2	2.99	
April 30, 1887	3.67	26	0.13	1	0.35	17
				3	0.86	
September 7, 1908	5.74	48	0.94	2	0.86	21
October 28, 1909	1.29	26	0.11	1	0.31	14
				3	1.35	
March 8, 1910	4.54	27	0.25	1	0.20	14
		40	0.51	1	0.72	
				3	1.74	
September 10, 1910	2.01	35	0.31	1	0.03	27
		40	0.34	1	3.04	
August 30, 1914	2.18	46	0.20	1	0.06	25
				2	1.70	



inches in 30 days, and followed by 1.20 inch in 6 of the following 16 days. The maximum continuous dry period was 25 days, beginning in late August 1874.

TABLE 9

Some droughts at Philadelphia, Pa.

BEGAN	PRECIPITATION IN PREVIOUS 30 DAYS	TOTAL PRECIPITATION IN		SUBSEQUENT PRECIPITATION IN		MAXIMUM CONSECUTIVE DAYS WITH LESS THAN 0.01
		Days	Inches	Days	Inches	
October 11, 1874	8.88	38	0.22	1	0.13	29
		40	0.35	3	1.13	
December 7, 1877	3.70	23	T	6	0.70	23
August 22, 1881	1.51	19	0.01	1	0.20	18
September 1, 1884	4.30	28	0.09	2	0.11	22
		31	0.20	2	0.26	
		51	0.58	1	0.44	
June 8, 1894	9.88	16	0.02	1	0.12	10
		22	0.16	1	0.14	
		39	0.41	2	0.17	
		57	1.05	2	0.97	
October 14, 1895	1.91	17	0	1	1.32	17
October 26, 1905	4.06	29	0.16	1	0.12	10
		33	0.28	2	1.33	
September 7, 1908	5.00	21	T	1	0.67	21
October 3, 1908	2.01	21	0.06	7	1.62	11
August 21, 1909	3.17	20	T	1	1.59	20
April 30, 1913	6.89	16	0.03	2	0.51	14

A record period of 75 consecutive days without measurable precipitation occurred at Portland, Oregon, June 25 to September 5, 1914.

Another classification of drought periods is illustrated by the accompanying table of periods of 35 or more consecutive days between March 1 and September 30, when less than 0.25 inch in the 24 hours was recorded at Philadelphia.

The plates and tables illustrate the variability in occurrence and quantity of precipitation during deficient intervals. Such data are given much attention in studies of water supply, as they indicate the deficient periods to be provided for and the evaporation conditions to be anticipated.

TABLE 10

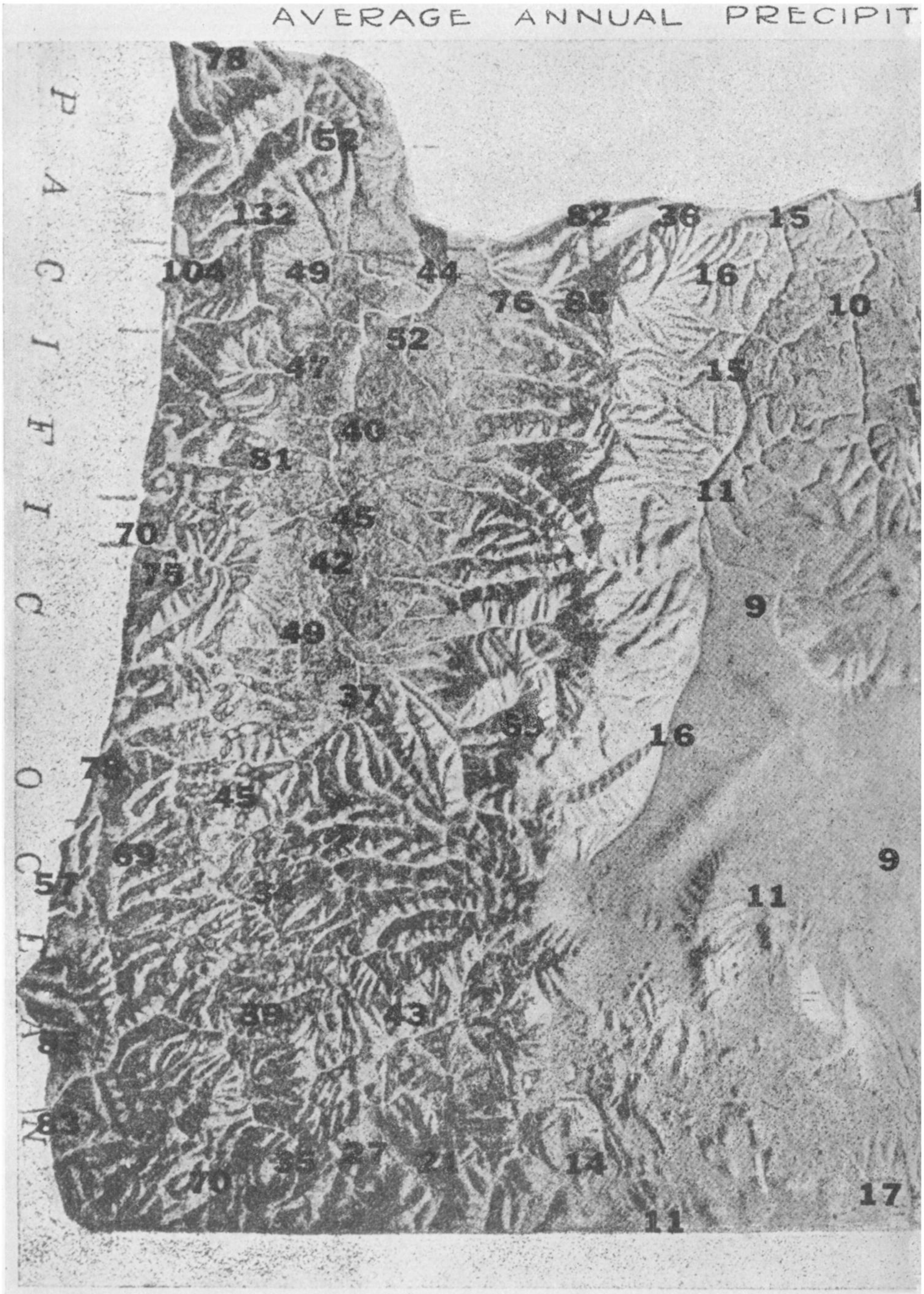
YEAR	INTERVAL	NUMBER OF DAYS
1877	July 30–September 5	38
1884	August 30–October 21	53
1885	February 26–April 3	37
1893	July 18–August 23	37
1894	June 7–August 2	57
1896	July 31–September 4	36
1906	August 30–October 3	35
1914	May 6–June 14	40

NOTE: When periods of 20 or more consecutive days were taken the maximum occurrence was in April.

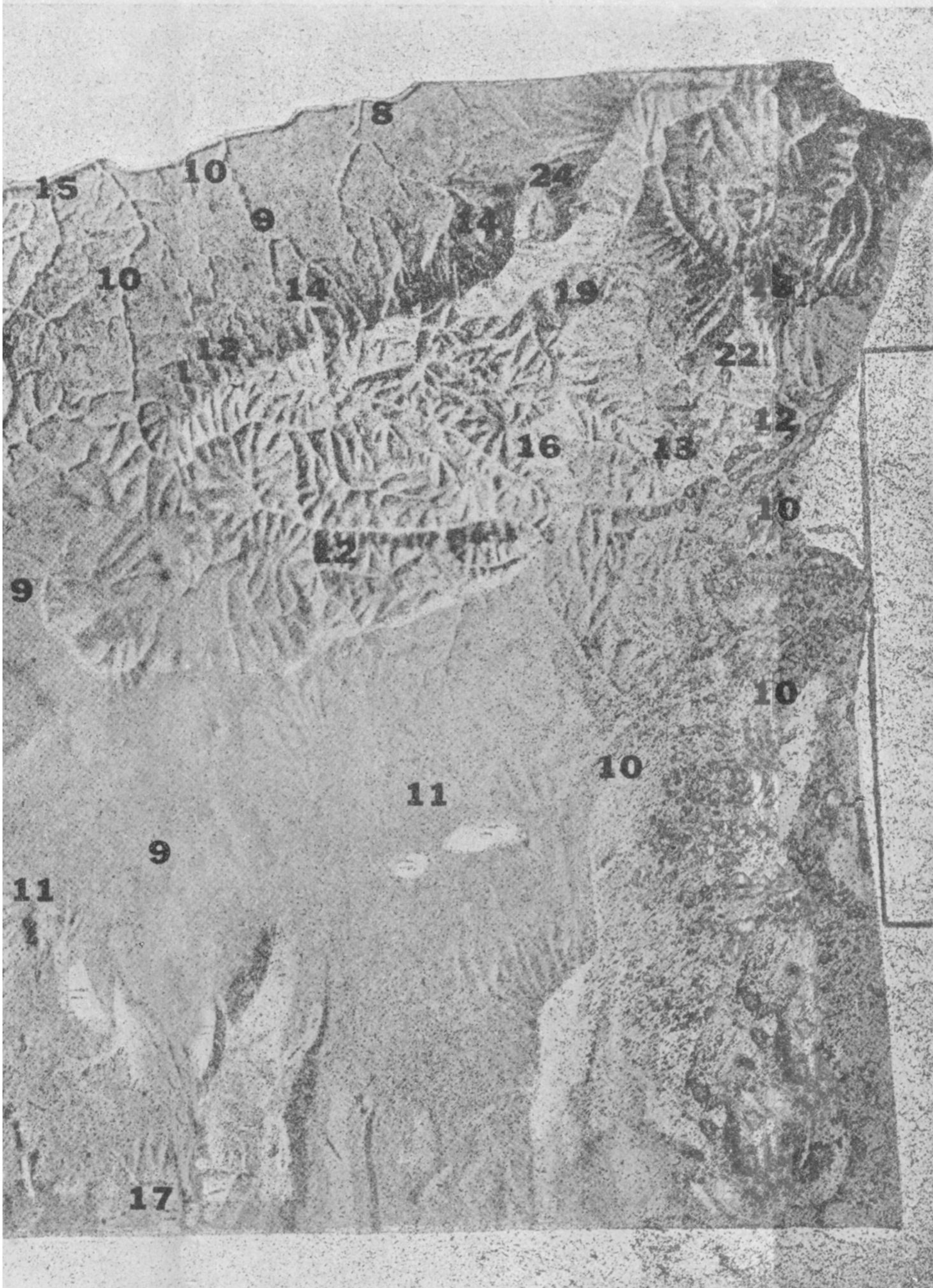
VARIATIONS OF PRECIPITATION WITH ALTITUDES

The Pacific Coast is the most notable example in the United States of the largely increased precipitation on the mountains adjacent to the ocean when the general wind direction is offsea, and this is illustrated on plates 31 and 32, which show the average precipitation for a number of years in Oregon, and for California in 1914 and March, 1915, and how the eastern slope of these mountains receives a notably decreased rainfall. The western slope of the Wasatch Mountains in Utah, with its precipitation in excess of that for the balance of the state, is interesting because of the greater distance from the ocean.

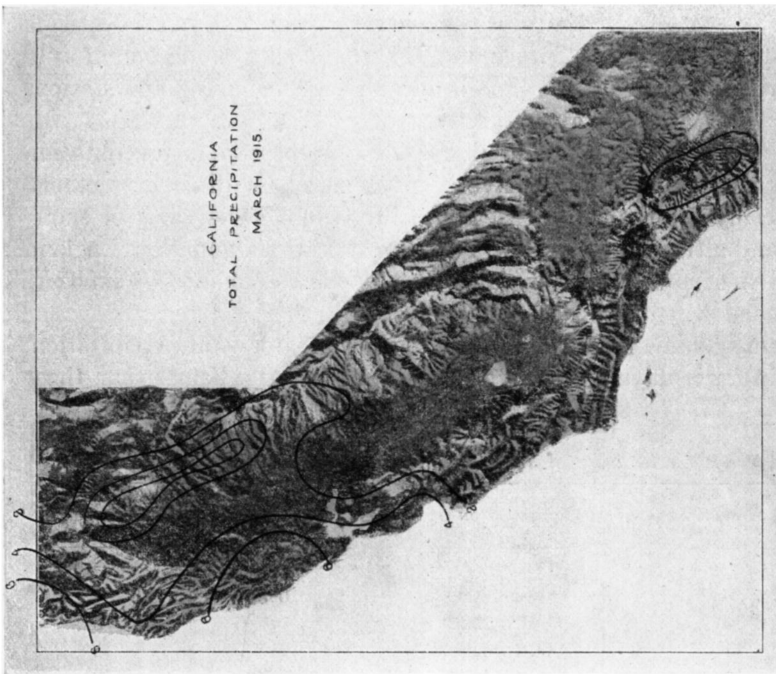
On the eastern coast Mount Washington stands as a notable instance, and the higher rainfall on the southern Alleghany Moun-


AVERAGE ANNUAL PRECIPIT
P A C I F I C O C E A N
78
52
132
104
49
44
82
36
15
16
76
10
52
47
15
40
81
11
45
70
42
75
9
49
37
16
45
69
57
9
11
43
83
27
21
14
70
11
17
Birkinbir

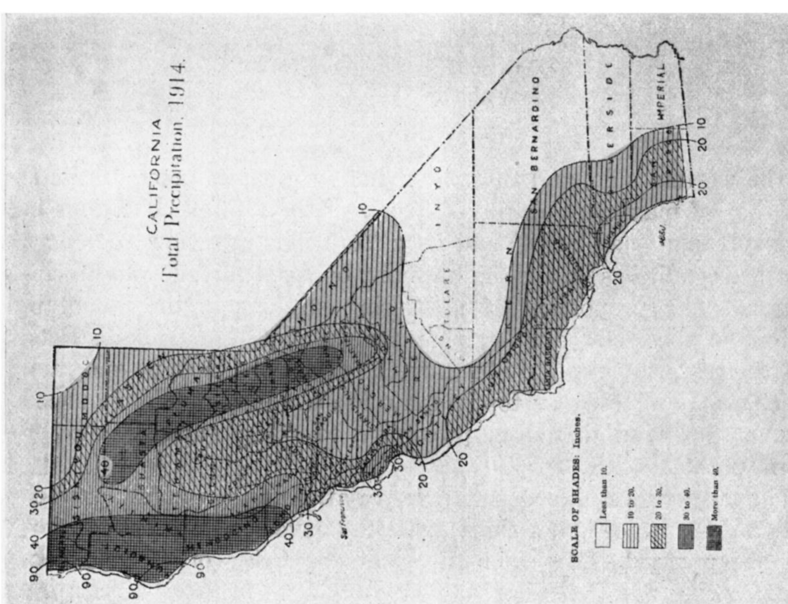
PRECIPITATION. OREGON.



Birkinbine. Variation in Precipitation. Plate.-31.



The influence of the diversified topography of California upon its precipitation is shown by the lines of equal rainfall in inches on the accompanying relief map.



Birkinbine Variations in Precipitations. Plate 32.

tains, especially in the more southern portion, is another specific example. Mr. R. R. Briggs, in 1914, compiled a tabulation of July records for 18 years of rainfall, and altitudes covering 104 stations in Arizona, which is given below.

A number of records and charts showing increase of precipitation with mountain altitudes have been prepared for different sections, especially for the Pacific Region. Mr. Brook's diagrams of snowfall and altitude across New York, West Virginia and New England show the increase of snow fall with altitude as modified by exposure to moist winds.

Pennsylvania records (see plate 4) show greater total precipitation, but in fewer days, for the stations east of the Alleghenies than those

TABLE 11

Average for 18 years of July rainfall at different altitudes in Arizona

NO. OF STATIONS	ELEVATION	AVERAGE RAINFALL	AVERAGE NUMBER RAINY DAYS
	feet	*inches*	
8	Below 1000	0.33	1
16	1000 to 2000	0.63	5
11	2000 to 3000	2.72	10
16	3000 to 4000	2.79	10
20	4000 to 5000	3.95	14
16	5000 to 6000	4.05	12
10	6000 to 7000	5.01	17
5	7000 to 8000	5.70	21
2	8000 or above	7.12	29

on the western side, and that the region of greatest precipitation is not that of maximum altitude. Study of the rainfall conditions in Pennsylvania (see plate 4) and New York illustrate how the effect of other conditions breaks the harmony between altitude and precipitation. The proportion of measuring stations in the mountain regions of these states is less than for the more populous districts, but there are sufficient to illustrate the variations in snow and rain, which, while affected by topography, are modified in a pronounced manner by wind direction, proximity to water surfaces and by storm paths.

The former idea of a considerable variation in the rainfall between the earth's surface and a short distance above seems to have generally disappeared. Mr. John E. Codman, C.E., of Philadelphia,

made a number of experiments some years ago with receiving vessels at different positions on a 50 foot mast, and concluded that the variations were due to counter-currents caused by the pole.

The city of Philadelphia for some years maintained a gauge at the ground surface, and adjacent to it an automatic gauge placed 13 feet above the earth. It was found that during storms with high winds the catchment of the elevated gauge was diminished by the roof of a building. Omitting occasions when such conditions occurred, the variation in quantities received by each was but a few hundredths for monthly totals, and such minute discrepancies may be caused by method of measurement in gauges of different type. The total difference of these two gauges was in some years less than that between measurements in different portions of the city.

At Columbus, Ohio, the Weather Bureau and the State University each maintain rain gauges, the former on the roof of an office building, and the latter on the ground in a open space three miles distant. The average monthly records for 29 years showed a monthly variation of the University gauge, referred to the Weather Bureau gauge as standard, of from -0.34 inch to $+0.20$ inch, and the average annual totals were 35.64 inches for the Weather Bureau Station and 36.16 inches for the University station, a difference of $1\frac{1}{2}$ per cent. Such discrepancies are small when the distance between gauges is considered, for this region receives severe storms over small areas.

It is evident that ill-chosen exposure on a roof will result in improper records because of air currents being changed by cornices, skylights, etc., and the naturally greater wind velocities in high elevations will produce some reduction by driving the rain on the gauge at a greater angle. The effect of winds in varying snow depths is exemplified in mountain regions, and in the "blizzard" type of snow storms. But it is difficult to accept any theory of radical differences, due to a few hundred feet of elevation alone, for any suggestion of humid air near the ground being absorbed by a rain drop in passage must be met by the query of how long the lower stratum of air can supply such additional moisture.

PERIODIC VARIATIONS

Considerable attention has been called to the theory of periodic changes in climate and to cycles of rainfall. Geological investigations have shown the existence in the past of climatic conditions

very diverse from those now prevailing, many of which are visible in topographical features.

A notable investigation on the variation in climate is that of Prof. Eduard Brückner, based upon oscillations in water surface of the Caspian, Black and Baltic Seas which vary with the heights of the rivers feeding them, the vintage season in south France, Germany and Switzerland subsequent to 1400, records of ice on rivers after 1738, occurrence of severe winters since 800, advances and recessions of Alpine glaciers for 400 years, temperatures in Europe and New England, and precipitation records of Europe and midland North America. These plotted up to 1865 showed an expected harmony between temperature and rainfall, and from the curves Professor Brückner deducted an average period for cycles of 35 years, the maxima of rainfall in the past century occurring in 1815, 1850 and 1880, and minima in 1830 and 1860.

Dr. Julius Hann had called attention to the variation in inland seas as early as 1867, and R. Sieger discussed secular variation in lakes in different regions. Muschketoff, Rossikoff and Brückner reviewed a quarter century ago the desiccation of lakes in Eastern Turkestan, Northern Caucasus and Western Siberia. C. K. Gilbert, in his monograph on Lake Bonneville (now Great Salt Lake), concluded that this had experienced 5 extended periods of high and low level, which had crests of extreme magnitude, and that the last was the presént stage of low and decreasing level, this was in 1890. Mr. L. H. Murdock in 1901 charted the water levels and precipitations at this lake, which indicated a harmony in the two curves, though his later records showed a more rapid diminution in water elevation than precipitation, explained by decreased catchment due to more extensive utilization of water by agricultural development. Mr. I. C. Russel's monograph on Lake Lahontan in Nevada deduced similar periods of level fluctuation.

Dr. Ellsworth Huntington has made exhaustive studies in portions of Asia and certain regions of the United States, Mexico and Guatemala. His work, "The Climatic Factor," presents much interesting data concerning the evidences of past climatic changes as typified by geology, archæology, history and botany.

Mr. E. E. Free, after a study of the Otero Basin in New Mexico, wrote,

> The whole history of Lake Otero and of the period since its disappearance is a record of great and continuous climate changes, with major fluctuations

indicated by the variations of the great ancient lake and its deposits. On these fluctuations are superposed many series of minor pulsations, the greater of which can be read in the triple record of changing topography in lake, dunes and arroyos.

Prof. E. A. Douglas and Dr. Huntington have made painstaking investigations into the thickness of annual rings of tree growth on specimens of yellow pine in Arizona and sequoia in California, covering periods of from 250 to 3150 years. Dr. Huntington corrected for age and longevity and used the data thus obtained as an index to past precipitation records. Huntington's resulting curve is reproduced by permission on plate 41, and gives a long continuous record of conditions at one region. The investigator has found a harmony between the growth of these trees and of the level of Owens Lake in California.

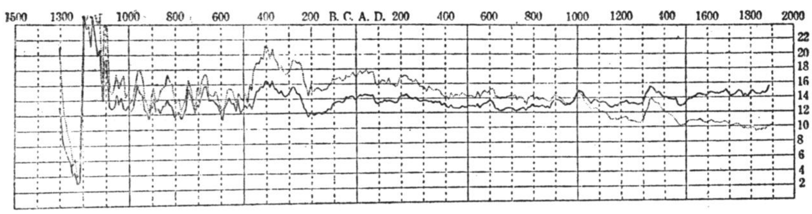


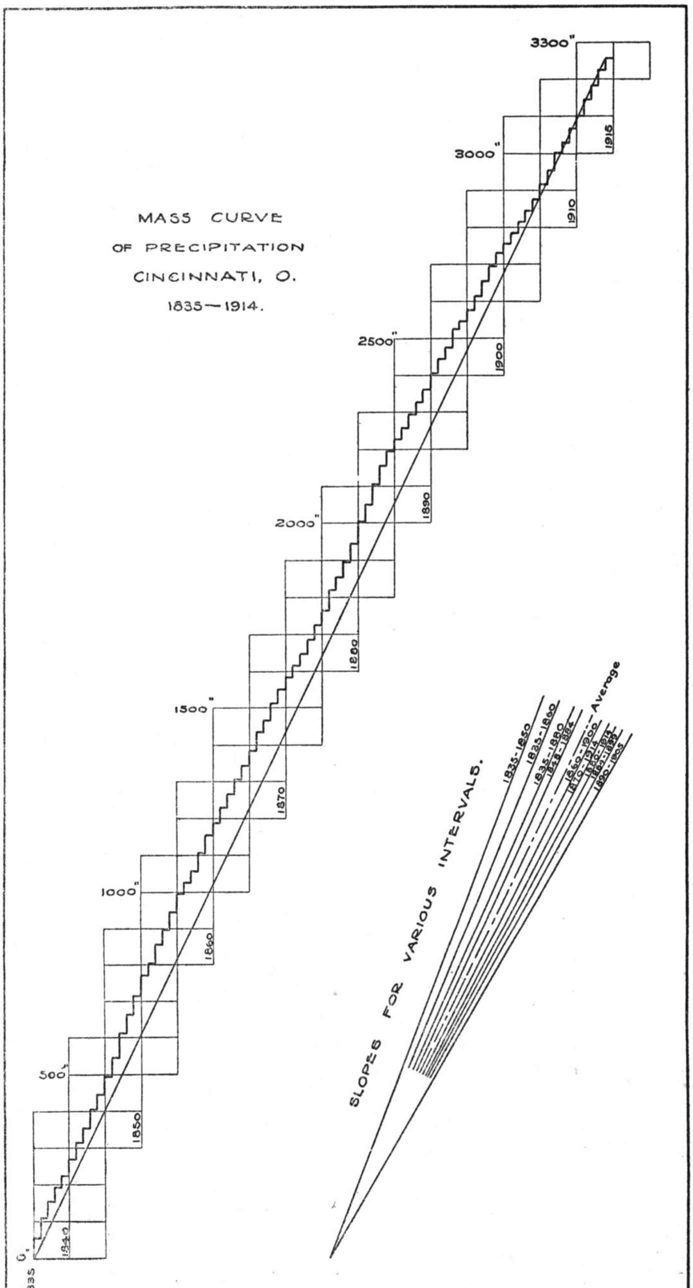
FIG. 38.—Curve of Growth of the *Sequoia washingtoniana* in California. Uncorrected (. . .) and Corrected (——). (See Table E, pp. 308–310.)

BIRKINBINE. VARIATIONS IN PRECIPITATION. PLATE 41.

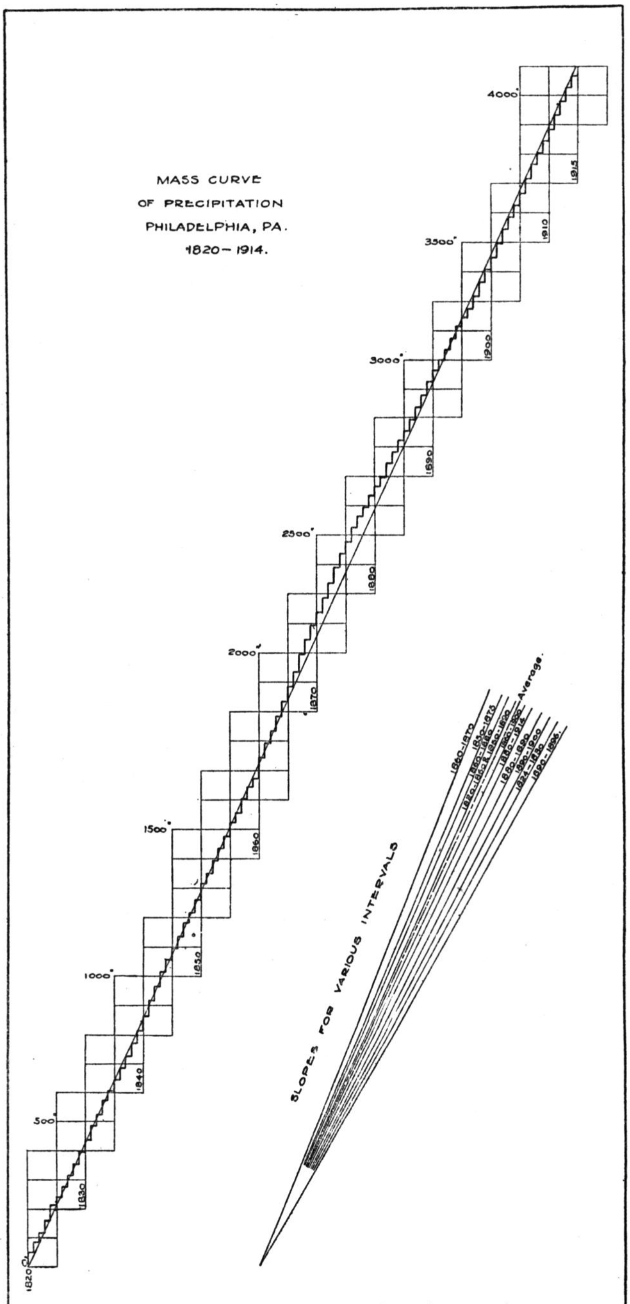
The growth of vegetation is affected by the material in which it roots and the occurrence of rainfall in the growing season, but such investigations offer another means of acquiring knowledge of past conditions.

Mr. W. M. Stewart's investigation of the annular rings of an oak at York, N. Y., with adjacent precipitation records at Rochester, covering 75 years, showed correspondence between growth and the quantity of rain in June and July, months included in the growing season of the oak. Huntington's investigations indicated that the precipitation in March, April and May were most closely related to the growth of the sequoia.

To illustrate the diversity of precipitation through different periods plates 35 and 37 have been prepared by plotting data in mass curves, above which are shown the slopes of increase for intervals of various durations. That the data used are mainly of one general region is because this offered most examples of long records. The mass curves



Birkinbine. Variations in Precipitation. Plate 35.


MASS CURVE
OF PRECIPITATION
PHILADELPHIA, PA.
1820 – 1914.
SLOPES FOR VARIOUS INTERVALS
Average
Birkinbine.- Variations in Precipitation Plate - 37

indicate by inspection marked variations, the slopes of increase for various intervals are shown, while any others desired may be taken by a straight line between points, or the total for any period, and from it the average, may be read by differences in ordinates.

Some method of adjustment is demanded to modify the use of the calendar year and to distribute the extremes; various methods being progressive averages for intervals of different length, determined by simple arithmetical means or by giving additional weight to the middle years of the period. Blanford's formula, $\frac{a + 4b + 6c + e}{16} = c'$, for 5 year intervals, has continued in favor among meteorologists.

The above mentioned studies, actual yearly totals, smoothed averages by various methods, and the charts on plate 38 show cycles irregular in periods and intensity.

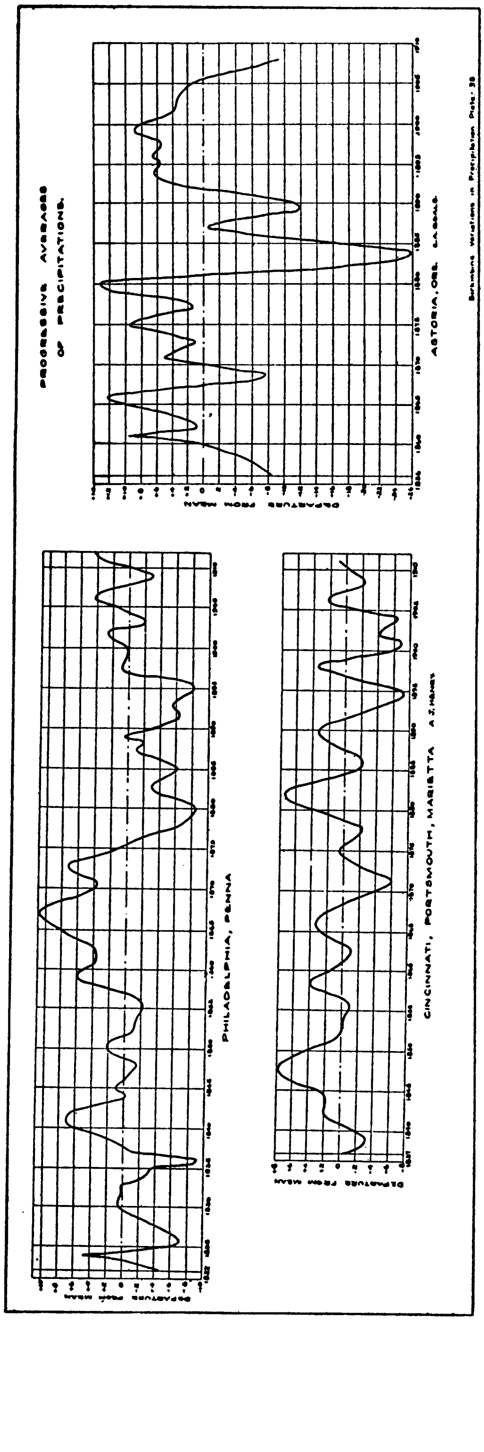
The curve for the Central Ohio region is according to Prof. A. J. Henry, and that of Astoria, Oregon, was prepared by Mr. E. A. Beals, who also evolved a similar curve for The Dalles, Oregon., which was more symmetrical than that for Astoria, and displayed a marked reduction in cyclic period for the later years. To include another region a curve for Philadelphia, Pennsylvania, which extends over a longer interval, has been computed and shown.

Professor Henry had, nearly 20 years ago, shown progressive averages of precipitation for south-eastern New England, the Ohio Valley and middle Mississippi Valley, which were later extended by Prof. D. W. Mead, who also showed similar curves for Wisconsin, San Joaquin Valley, California, and Charleston, South Carolina, and others have computed and plotted curves for specific localities and by various methods.

Regional data are preferable, where conditions permit for general studies, as the irregularities due to severe rains recording heavily at one gauge and passing beyond another are thus compensated for.

When a number of curves, smoothed by the same method, are plotted to uniform scale, there will be some instances of harmony shown; however, any general agreement is not to be expected, as the variations in precipitations are local, not general, and are due to various causes that are distinctly non-uniform in extent of area or time.

Local conditions are subjected to too many causes to permit their adherence to a general rule; also, any modifications of pressure at one place would naturally produce converse conditions at another


PROGRESSIVE AVERAGES
OF PRECIPITATIONS.
DEPARTURE FROM MEAN
ASTORIA, ORE.
PHILADELPHIA, PENNA
CINCINNATI, PORTSMOUTH, MARIETTA
DEPARTURE FROM MEAN
DEPARTURE FROM MEAN

locality, so that abnormal features at one point mean subnormal at another.

The northwestern portion of the country exhibits a peculiar tendency to 3 year intervals between high years and between low years, as shown by the records of Portland and Roseburg, Oregon, and Spokane and Seattle, Washington, whose individual records show a variation in magnitude between both high and low periods for different occasions.

The San Francisco records have been interpreted as subject to the full cycle periods, approximating 12 years, and cycles of different extent have been suspected at other localities.

The sunspots, with their 11 year period, have been frequently utilized in search for a harmony with climatic and meteorological conditions, on the basis of less solar radiation, and hence less precipitation with increase of sunspots. Professor Humphreys mentions the general inverse relation between sunspots and the average temperature of the earth as a whole, and the modification due to the quantity of volcanic dust in the upper atmosphere.

Prof. F. H. Bigelow found that temperature curves varied directly with sunspot curves on the Pacific Coast, inversely in the West Gulf States, and were indifferent to them in northern Arizona. Of this subject he wrote: "The numerous studies during the past 50 years into the apparent synchronism between the solar variations of energy and the terrestrial effects, as shown in the magnetic field and the meteorological elements, have been on the whole unsatisfactory, if not disappointing. Just enough simultaneous variation has been detected in the atmosphere of the sun and the earth to fascinate the attentive student. * * * Discussions of the spots are being replaced by others upon the solar prominences and faculae, which respond much more exactly to the working of the sun's internal circulation. * * * It is perfectly evident that if secular variations of any kind, such as the annual changes in terrestrial pressure, temperature or the magnetic field, are to be attributed to solar action, the original observations must be finally reduced to a homogeneous system. The local peculiarities of each station must be carefully eliminated, and the data of numerous stations must be concentrated before anything like quantitative cosmical residuals can be obtained. * * * The skeptical attitude of conservative students, who declare that the many indecisive results already obtained mean that there is no true and causal solar-terrestrial syn-

chronism, is of course quite fallacious until it has been demonstrated by the use of first class homogeneous data that the suspected physical connection is imaginary."

Dr. Hann wrote: "The results of very numerous and complex investigations of the connection of the sunspot period with variations in the meteorological elements have not wholly corresponded to expectations. * * * There can be no thought of the prediction of the weather on the ground of the sunspot cycle."[3]

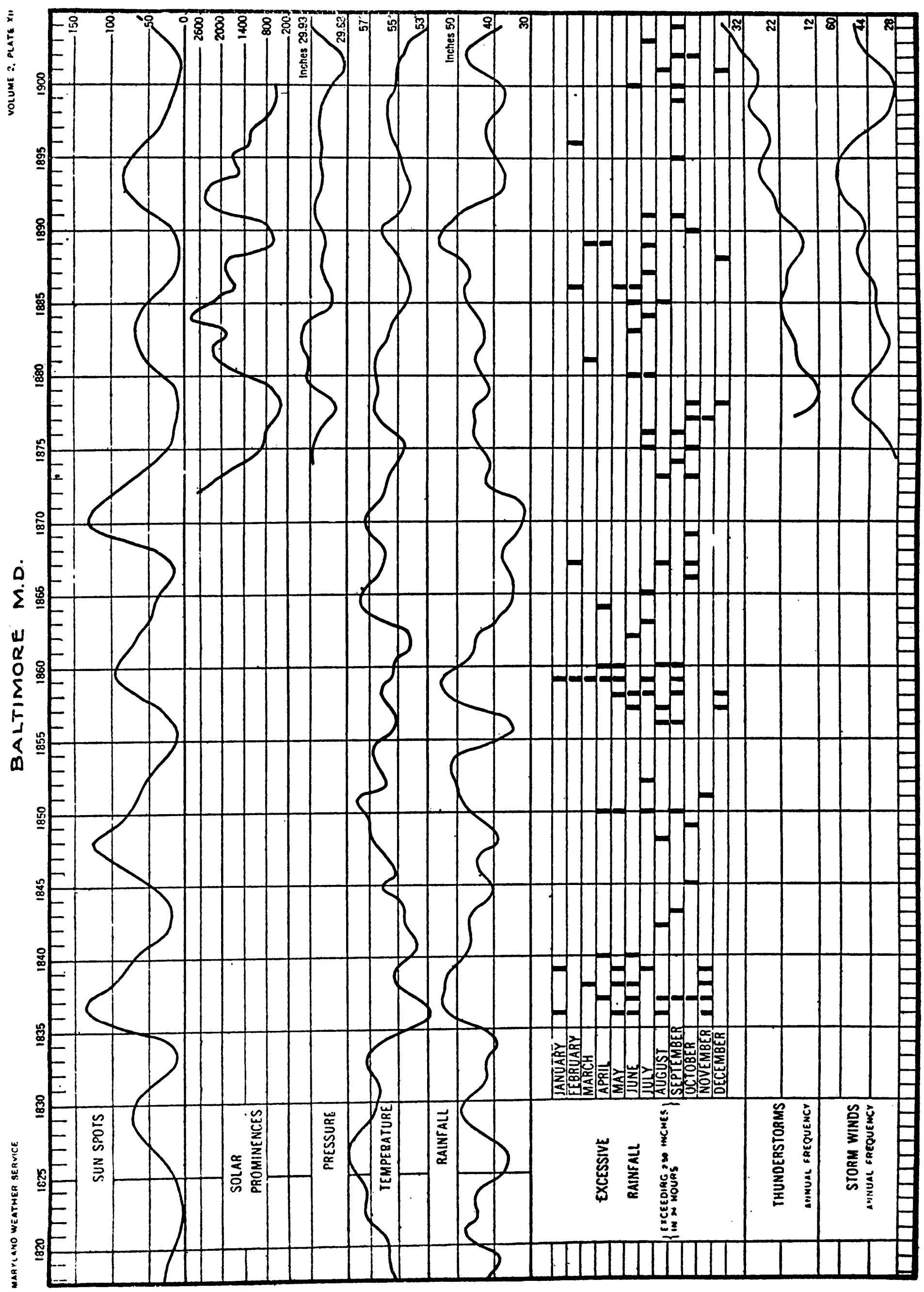
Professor Fassig plotted data up to 1904, using Wolf's data of sunspots and solar prominences, and also the Baltimore annual data of pressure, temperature, total rainfalls, number of thunderstorms, and frequency of storm winds exceeding 25 miles per hour, the curves of Baltimore data being smoothed by the formula $\frac{a+2b+c}{4} = b'$, a, b, and c being actual values for 3 successive years. The rainfalls greater than $2\frac{1}{2}$ inches in 24 hours were also plotted, and his chart, reproduced by permission, illustrates the variation shown in the different curves. (See plate 39.)

Assumptions that other agencies in the solar system appreciably affect the quantity of moisture received have fallen to the rear as actual meteorological knowledge has advanced. To illustrate the minor effects of such, Professor Humphreys has calculated that the planets by gravitational action could produce perturbations in the earth's orbit which occasionally, under the most favorable circumstances, could alter the actual surface temperature by as much as 0.02°F., and that an equal difference may be brought about by the varying distance of the earth from the sun as the earth and moon rotate about their common center of gravity.

Professor Fassig, referring to the records of maximum 24 hours precipitation at Baltimore, Maryland, for each year from 1871 to 1903 said: "The tendency to a periodic fluctuation embracing a group of years is more marked than in those representing the total seasonal or annual fall." This is an interesting case, but is to be taken as a single example.

Prof. A. J. Henry wrote in 1913: "Since systematic observations began there has not been a single year when precipitation was above normal in all parts of the country, and but one year when it was deficient in all parts of the country in one and the same year. The

[3] This was written before the researches and studies of Arctowski.



SUNSPOTS, SOLAR PROMINENCES AND WEATHER CONDITIONS.

(Smoothed annual values for weather conditions, excepting, excessive rainfalls, which are observed values.)

COURTESY O.L. FASSIG.

Plate.-39

Birkinbine. Variations in Precipitation

abnormalities for the smaller climatic units, since the units are of unequal size, do not readily lend themselves to a combination, but considered separately, they indicate the interesting fact that in the Rocky Mountain Region, from Montana southward to the Mexican border, the number of years with precipitation above the normal is very nearly equal to the number of years with precipitation below the normal. East of the Mississippi, and in the Gulf and South Atlantic States especially, the number of years with diminished precipitation is in a very decided majority. Further, it would seem that years of fat or lean precipitation do not follow any recognizable sequence, and that the most probable value for any year is not the arithmetical mean or normal for the latitude, but a value near but slightly below the mean. On the other hand years of excessive rainfall do not occur with the same frequency as years of light rainfall; heavy rains seem to be due to extraordinary and probably worldwide temperature and pressure relations, which appear to be the cause of unusual storm movement with its attendant precipitation. Thus, in 1912, the prevalence of an unusually large number of south-west storms and the rains attending them produced the great flood in the lower Mississippi Valley of 1912. The calendar year is much too great a unit for comparative purposes. Unfortunately the labor of assembling the data in a more convenient form is so great as to be prohibitive."

Doctor Hann, in discussing the inconstant distribution of the climatic elements, said: "There are at least certain fluctuations about a common mean, even if no progressive changes in a given direction take place."

Many investigators and meteorologists discredit any supposed climatic changes in a century or two, although the disposition to cyclicism is recognized as well as the irregularities.

Artificial conditions, produced by man, may be charged with some differences in visible effects of precipitation. The increased flood heights, due to constriction and obstruction of stream channels, has at some localities reached a stage requiring preventive legislation or compensating improvements. The extended use and too frequent waste of ground waters has drawn heavily on many subsurface basins, and storage dams for their different uses, artificially change the natural stream discharge and often cut off an underchannel and subsoil flow. Slight changes in character and amount of precipitation are sometimes claimed to occur with agricultural

development and deforestation, while the runoff is materially affected by such factors.

But that an actual and appreciable change in climate, temperature and precipitation conditions is now in effect has not been determined to the satisfaction of those who have made exhaustive studies.

CONCLUSIONS

The economic considerations of engineering are recognized when these do not conflict with safety. The construction and operation of water works are more than a financial investment or a convenience; for not only the comfort and development of a community, but also its health and life are affected. Consequently, protective and preventive measures against interruption or destruction must be made with a wider margin than for such engineering works as are merely business improvements.

That the many variations of precipitation which furnishes the supply have been properly considered and met by engineers is attested by the large number of plants in successful operation. That each instance is a special problem is one of the pleasing features of engineering work, and it is hoped that this paper will encourage the distribution of data concerning unusual conditions that are of interest and value to the profession.

DISCUSSION

Mr. William W. Brush: Mr. Birkinbine has collected such a vast amount of material that it is impossible to discuss his paper as a whole. The speaker had an opportunity to read the greater part of the paper, and thought it might be of interest to point out the variation in the amount of water available as a result of precipitation in a watershed from which the supply was drawn from the subsurface water levels, and in a watershed where it was drawn from surface runoff.

The distance between the Croton watershed and the Long Island watershed is only about 45 miles. The rainfall conditions are usually similar, although, as has been shown, the Croton precipitation is greater than the Long Island. The runoff conditions are entirely different, the Long Island watershed being an extremely pervious soil, mainly sands and gravels, with some clay at varying

depths. The greater part of the rainfall reaches the underground water table, only a small portion appearing in the streams which form in slight depressions on the south side of the Island, where the surface of the ground dips below the water table. The Croton watershed is composed of a typical mixture of various soils usually found in a hilly country, there being no well defined underground water table. The rainfall usually has but a short distance to travel before it reaches a stream.

At the end of the drought period extending from July 1910 to July 1911 there was a very heavy precipitation, especially in the month of August, on the two watersheds. This precipitation on the Brooklyn watershed amounted to 10 inches; on the Croton watershed it was a little over 8 inches. It was followed in September with precipitation of 2 inches and in October about 6 inches.

The total underground flow on the Long Island watershed has never been determined; but the best data available to determine the underground flow at any particular part of the watershed are from the yield of an infiltration gallery, which, at Wantagh, Long Island, is made up of about 12,000 feet of pipe laid 5 to 14 feet below the normal water table at right angles to the direction of flow. This gallery, when operated, takes practically the entire flow of the underground water table above the clay bed, which is approximately 100 feet below the surface. In the summer of 1911 the Wantagh gallery showed a reaction of from 15 to 20 per cent in yield from July to October, the low yield being in the month of October, in spite of the high rainfall period for the months of August, September and October. On the Croton watershed, with a surface runoff, the runoff in July amounted to 25,000,000 gallons per day, whereas, by October it had increased to over 600,000,000 gallons per day, or about 2500 per cent. With the surface supply of Long Island the yield may not increase for several months after the drought has been broken by copious rainfall, due to the rainfall on the greater part of the watershed not reaching the collecting works until months have elapsed. On a surface watershed like the Croton there is a very rapid augmentation in flow from a heavy rainfall, following a prolonged drought, the water only taking a few hours to reach the various streams, and the soil soon becoming sufficiently moistened to rapidly give up additional rainfall.

Mr. Andrew J. Provost, Jr.: Too much credit can hardly be given to the painstaking care and excessive labor employed by the

author in the presentation of the data which form the framework of this paper. It is unquestionably an important contribution to hydraulic engineering.

Although the author disclaims a purpose for his paper outside of an academic discussion of variations in precipitation, the data which he presents are worthy of further consideration in the manner and extent to which they may affect engineering design.

Water is, of course, the most important to man of the national resources, and the manner in which it is supplied for his uses is equally important. Nature is so capricious in this respect that man's ingenuity has been constantly taxed not only to conserve by regulation so that his needs may be at all times supplied, but also to safeguard his life and property from destructive oversupply. Drought and flood have probably, since the beginning, been as destructive to the human race as war and pestilence.

It is only during the past one hundred years or so in this country that records of rainfall have been observed or preserved, and there are only a few instances that cover more than a few decades. Most of these records, except very recently, furnish no data except the daily precipitation or the total for a storm. Measurements of intense rainfalls for short periods have bearing upon many important engineering designs, and it is to be regretted that the information available is so relatively meagre. Since the recent general use of automatic registering rain gauges a large amount of valuable data has been collected by various institutions and municipalities, and it is highly important that these results be made available to engineers.

The speaker has contributed, at the request of the author, and in amplification of his paper, a few tables and diagrams, to which he desires to add a very brief discussion of the uses of this kind of data in engineering design.

Table 1 indicates in a general way some of the more extended series of rainfall observations which have been preserved. These results are tabulated as average monthly precipitations over the entire periods of observation. Such records are of great value in the design of water works collecting basins and for determining the areas of watersheds required for a given supply. Records of this nature should be supplemented by diagrams similar to plates 5 and 6 of the author's paper. These show the maxinum, average and minimum precipitation at various places. The following diagram com-

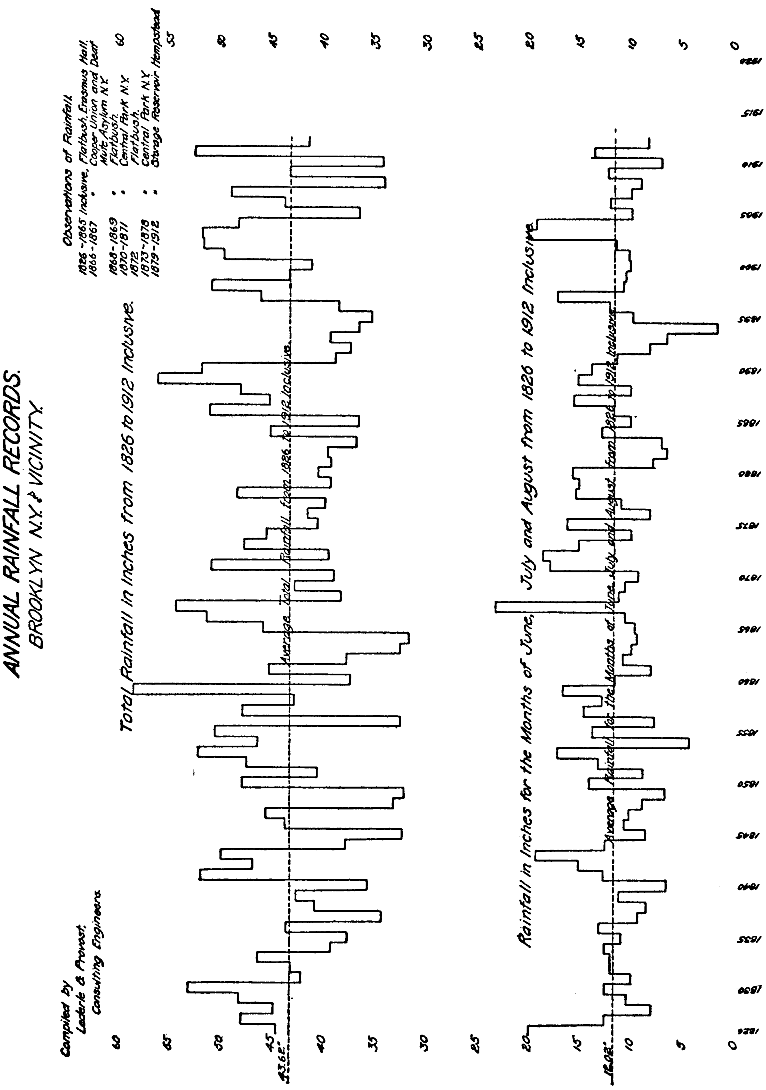

ANNUAL RAINFALL RECORDS.
BROOKLYN N.Y. & VICINITY.
Compiled by
Lederle & Provost,
Consulting Engineers.
Observations of Rainfall.
1826-1865 Inclusive, Flatbush, Erasmus Hall.
1866-1867 " Cooper Union and Deaf Mute Asylum N.Y.
1868-1869 " Flatbush.
1870-1871 " Central Park N.Y.
1872 Flatbush.
1873-1878 " Central Park N.Y.
1879-1912 " Storage Reservoir Hempstead
Total Rainfall in Inches from 1826 to 1912 Inclusive.
Average Total Rainfall from 1826 to 1912 Inclusive.
43.62"
Rainfall in Inches for the Months of June, July and August from 1826 to 1912 Inclusive.
Average Rainfall for the Months of June, July and August from 1826 to 1912 Inclusive.
12.02"

TABLE 1

Rainfall observations, various localities, extending over long periods. Average monthly precipitation, inches. Compiled by Lederle and Provost, Consulting Engineers

LOCATION	GAUGE ELEVATION	PERIOD	JAN.	FEB.	MAR.	APR.	MAY	JUNE	JULY	AUG.	SEPT.	OCT.	NOV.	DEC.	TOTAL
	feet														
New York City, Central Park....	97	1836–1913	3.40	3.48	3.76	3.56	3.89	3.73	4.12	4.61	3.68	3.85	3.54	3.67	45.29
Croton Water Shed, Various Gauges.........	200–600	1868–1909	4.15	4.11	4.25	3.49	3.86	3.57	4.71	4.94	4.24	3.99	3.65	3.96	48.92
Rochester, N. Y...		1872–1914	3.08	2.07	2.98	2.47	2.92	2.90	3.12	2.96	2.38	2.78	2.57	2.79	33.69
Long Island, N. Y., Various Gauges.........	30–50	1826–1902	3.29	3.21	3.52	3.35	3.64	3.35	3.99	4.12	3.40	3.62	3.69	3.38	42.56
Boston, Mass., Roxbury........		1818–1914	3.70	3.49	4.10	3.81	3.56	3.10	3.47	4.01	3.37	3.62	4.06	3.74	44.10
Cambridge, Mass. Harvard College	75	1841–1913	3.97	3.55	3.97	3.62	3.41	3.13	3.34	4.23	3.54	3.55	3.99	3.56	43.86
New Bedford, Mass............	100	1814–1913	4.01	3.88	4.34	3.95	3.96	3.07	3.23	4.17	3.54	3.94	4.24	4.15	46.47
Lowell, Mass......	80	1826–1913	3.18	3.12	3.56	3.48	3.49	3.28	3.53	4.24	3.37	3.59	3.72	3.36	41.92
Waltham, Mass....	30	1825–1913	3.34	2.90	3.69	3.76	3.55	3.15	3.63	4.24	3.48	3.74	3.98	3.28	42.74
Providence, R. I...	163	1832–1913	4.07	3.85	4.19	3.77	3.64	3.19	3.26	4.03	3.35	3.67	3.98	4.01	45.01
Middletown, Conn...........	125	1858–1913	4.12	4.12	4.66	3.54	3.76	3.37	4.04	4.67	3.64	4.19	3.97	3.97	48.05
New Haven, Conn.	107	1804–1829 1864–1913	3.78	3.98	4.11	3.51	3.88	3.07	4.32	4.57	3.64	3.86	3.61	3.64	45.97
Burlington, Vt....	404	1828–1913	1.85	1.64	2.03	2.01	3.08	3.40	3.96	3.48	3.59	3.25	2.54	1.93	32.76
Hanover, N. H., Dartmouth College.........	603	1835–1913	2.67	2.72	3.21	2.50	3.19	2.89	3.69	4.02	3.56	2.88	2.71	2.97	37.01
St. Paul, Minn....		1837–1912	0.94	0.86	1.38	2.29	3.37	4.01	3.48	3.37	3.30	2.06	1.35	0.99	27.41
Albany, N. Y.....	97	1826–1913	2.59	2.44	2.75	2.64	3.50	3.95	4.04	3.77	3.33	3.41	2.93	2.63	37.98

piled by the speaker is for the same purpose. Records of this kind are most illuminating when reduced to diagrammatic form. The proportional extremes of annual precipitation in various places, as shown by the author in table 1, may be amplified by showing the percentage of maximum and minimum precipitation to the mean over extended period, as follows:

LOCATION	PERIOD	PER CENT OF MEAN	
		Maximum	Minimum
	years		
Boston, Mass.	96	153	62
Detroit, Mich.	43	149	66
Little Rock, Ark.	34	154	68
New Orleans, La.	78	153	55
Omaha, Neb.	43	165	52
Richmond, Va.	42	173	66
Rochester, N. Y.	43	148	60
St. Louis, Mo.	77	172	59
St. Paul, Minn.	77	182	37
Brooklyn, N. Y.	87	135	73

The Brooklyn record also shows that for three successive years during the period of 87 years, the minimum rain fall was only 78 per cent of the mean for the entire period.

For special purposes, such as spillway design, it is of greatest importance that accurate information exist regarding the maximum rates of precipitation, so that full provision may be made for disposing of surplus water with safety to the structures. For small watersheds with steep slopes and generally impervious surfaces it is necessary to provide spillway capacity for substantially all the rainfall from a short intense storm. Data of this character are also of greatest importance for the proper design of storm water sewers and culverts. Some records of intense rainfall in addition to those mentioned by the author are shown in table 2.

Data of this character were not available prior to about twenty-five years ago, and to this fact is due, in a great measure, the large aggregate damages to property which have resulted from inadequate structures.

An interesting fact alluded to by the author is the effect of intense precipitation upon the physical and sanitary character of the

TABLE 2

Records of intense rainfall. Total precipitation and rate in inches per hour during various periods. Lederle and Provost, Consulting Engineers

LOCATION	DATE	PERIOD IN MINUTES 5		10		15		20		30		40		50		60		120		TOTAL IN 1 DAY
		Total	Rate	Total	Rate	Total	Rate	Total	Rate	Total	Rate	Total	Rate	Total	Rate	Total	Rate	Total	Rate	
New York City:																				
Manhattan	July 10, 1915	0.7	8.9	1.3	7.6	1.6	6.5			2.1	4.2					2.3	2.3	2.6	1.3	2.74
Manhattan	July 28, 1913	0.5	6.1	1.0	5.8	1.2	4.8			1.5	3.0					2.7	2.7	3.1	1.6	3.11
Manhattan	September 5, 1913	0.6	7.2	1.2	6.9	1.6	6.4			2.6	5.2					3.3	3.3	3.7	1.9	4.14
Staten Island	October 1, 1913		6.0		5.6		5.2		5.1					3.8	4.6		4.4	6.2	3.1	7.54
Brooklyn	June 10, 1911			0.5	3.1			0.6	1.7	0.6	1.2									
Brooklyn	1907–1911				2.6				2.3		1.7		1.5		1.2		1.3		0.8	5.58
Erie, Pa.	August 3, 1913	0.4	4.7	0.7	3.5	0.9	3.5			1.4	2.8					1.5	1.5	2.8	1.4	
Columbus, O.	1897–1914	0.6	6.8	0.9	6.0	1.3	5.1	1.5	4.6	1.9	3.8	2.0	3.5	2.6	3.1	2.7	2.7		1.1	
Cincinnati, O.	July 7, 1915	0.5	6.5	0.7	4.2															
St. Louis, Mo.	July 14, 1912															3.0	3.0		0.9	10.2
	August 19, 1915																			
Kansas City, Mo.	Various		6.5		4.5		4.0		3.6		3.3		3.0				2.4			7.0
Galveston, Tex.	1898–1913				6.0	1.0	4.0		5.5		5.0		5.0		5.5		5.0	6.3	3.2	14.4
New Orleans, La.	September 29, 1915	0.3	3.6	0.6	3.6	0.7	2.8			1.1	2.2					1.7	1.7	2.5	1.3	
St. Petersburg, Fla.	August 2, 1915																			15.5

runoff, and the complications which are added to the treatment of the runoff at such times for the removal of physical and sanitary impurities. An instance of this kind is Esopus Creek, New York, which has a drainage area of abut 240 square miles, an average discharge of about 550 second feet, and an average summer flow, July and August, of about 90 second feet. The shed is in general sparsely populated, with the dwellings for the most part near the principal streams. In summer there is a large vacation population. Most of the buildings are provided with privies. The average characteristics of the main stream include:

Turbidity	about 7 parts per million
Color	about 6 parts per million
Chlorine	about 2 parts per million

Bacteria at 20°C	about	1,000 to 5,000 per cc. in summer
Bacteria at 40°C	about	100 to 1,000 per cc. in summer
B. Coli	about	10 to 100 per cc. in summer

These general characteristics obtained in June and July, 1914. On August 11 and 12, 1914, considerable precipitation occurred on this shed after about two weeks drought. Samples of stream water collected August 12 showed:

Turbidity	500 to 600 parts per million
Color	25 to 30 parts per million
Chlorine	4 to 6 parts per million

Bacteria at 20°C	about	50,000 to 230,000 per cc.
Bacteria at 40°C	about	20,000 to 60,000 per cc.
B. Coli	about	1,000 to 10,000 per cc.

These comparative analyses indicate clearly the pronounced effect of rapid runoff, under certain conditions, in temporarily changing the sanitary character of a stream.

Another important phenomenon of rainfall, and one which is not specially emphasized by the author, is the proportional rates and quantities, extending over considerable periods. A study of the records of the New York City Meteorological Observatory, over a period of forty-five years, shows that the greater part of the total annual precipitation occurs at the higher rates and during a relatively small portion of the total storm period. In other words, the greater part of the aggregate storm period is confined to light

rains which contribute much less than half of the total volume of the annual precipitation. This is illustrated in tables 3, 4 and 5 which cover a period of three years. These tables are based on the total amount of measured rainfall during each hour when precipita-

TABLE 3

Rainfall phenomena, New York City, proportional distribution. Proportion of aggregate storm period 1911 to 1913 inclusive, when certain rates of precipitation were exceeded. Lederle and Provost, Consulting Engineers. July, 1914.

YEAR	PER CENT OF STORM PERIOD WHEN RATES IN INCHES PER HOUR EXCEEDED				
	Trace	0.03 inch	0.1 inch	0.2 inch	0.3 inch
	per cent	*per cent*	*per cent*	*per cent*	*per cent*
1911.........	100	59.10	15.10	4.85	2.50
1912.........	100	31.50	14.00	5.21	2.60
1913.........	100	64.40	15.80	7.06	3.93
Average...	100	51.50	15.20	5.72	3.00

TABLE 4

Proportion of annual precipitation 1911 to 1913 inclusive, falling at rates exceeding above rates

YEAR	PER CENT OF ANNUAL PRECIPITATION AT RATES EXCEEDING				
	Trace	0.03 inch	0.1 inch	0.2 inch	0.3 inch
	per cent	*per cent*	*per cent*	*per cent*	*per cent*
1911.........	100	88.60	55.80	30.80	21.90
1912.........	100	80.80	62.60	37.90	24.20
1913.........	100	91.40	70.70	51.60	40.00
Average...	100	87.40	63.00	40.80	28.70

TABLE 5

YEAR	PROPORTION OF YEAR WHEN PRECIPITATION EXCEEDED RATES OF				
	Trace	0.03 inch	0.1 inch	0.2 inch	0.3 inch
	per cent	*per cent*	*per cent*	*per cent*	*per cent*
1911.........	9.40	5.60	1.50	0.46	0.24
1912.........	9.80	3.10	1.40	0.51	0.25
1913.........	9.90	6.40	1.50	0.70	0.39
Average...	9.70	5.00	1.47	0.56	0.29

tion occurred, and do not include more intense rates for a period less than one hour, the data for which are not available. The tabular results show that for the years cited only 15 per cent of the storm period exceeded an hourly rate of 0.1 of an inch, and that during this brief period 63 per cent of the total annual rainfall was precipitated. If, instead of expressing these periods in percentage of storm period, as in table 4, we convert them into parts of the entire year, the results appear as in table 5, which shows by comparison that 63 per cent of the average annual precipitation for these three years (50.74 inches), amounting to 32 inches, was confined to an aggregate period of about five and one-half days (131 hours), and that over 40 per cent (20.7 inches) fell during periods aggregating about two days (49 hours).

This phenomenon, while interesting in many ways to water works engineers, has its most complete application perhaps to designs involving diversion of storm water from combined sewers connected to sewage treatment works. In the absence of data of this kind it has been the practice in the past for boards exercising governmental control in the design of sewerage systems, to insist upon the treatment of a much greater amount of storm water than appears upon close examination to be warranted in some cases. As an example it may be suggested that where the discharge of sewage is to be made into a large tidal estuary or other stream not used for potable purposes, the general sanitary character of such stream would not be ordinarily affected by the discharge of a portion of the sewage diluted with a relatively large amount of rainwater, during 5 per cent of the time, or about one and one-half days per month. This result could ordinarily be obtained in this locality by providing for the treatment of all surface water resulting from rainfall rates less than 0.03 of an inch per hour, and without, as a rule, materially increasing the cost of the treatment works to be provided.

In conclusion it may be said that most of the data relating to variations in precipitation and other rainfall phenomena now available in useful form have been compiled and arranged by engineers who could ill afford to spend the time required on this exhaustive research. It seems important that engineers should clearly designate the nature of the meteorological information which is required for their work in order that the observed results may be compiled and published in most useful form.

Credit should be given to Mr. Goodnough, Chief Engineer, Massa-

chusetts State Board of Health, for his recent valuable contributions with respect to extended rainfall records in New England.

MR. FRANCIS F. LONGLEY: Mr. Birkinbine presented one very striking diagram of the excessive runoff of the Ohio watershed in 1913, and made a comment in connection with it that it was the greatest rainfall that had taken place there. By that he no doubt meant that it was the greatest rainfall there of which there was any record. It is undoubtedly true that a great many people lose sight of the fact that the largest or smallest rainfall shown in the record of a station is probably not the largest or smallest that has ever occurred, or might ever occur, at that station. In other words, the longer the time you take for consideration of a record, the greater the maximum and the smaller the minimum is likely to be.

Our office has in the last year or so been studying the matter of variation of rainfall on the basis of probabilities, and it leads to some rather interesting possibilities in the way of predicting what the maximum or minimum rainfall may be. It does not enable one to say what the rainfall will be next year or the year after, but it does enable one to say with some degree of confidence what maximum or what minimum is liable to occur in a period of a given length.

The seasonal variation of rainfall may easily be obtained from records. The variations in annual rainfall are not so easily obtainable. It is desirable to put variations of rainfall on a comparative basis which eliminates absolute values and states things in relative values. The author of the paper made a strong point of that. This can be done in the matter of rainfall records by resorting to the principles of probabilities, and stating variations in terms of the coefficient of variation. This coefficient of variation has a definite meaning in the theory of statistics, and knowing the mean annual rainfall for a period of years, and determining the coefficient for that record of rainfall, it is a reasonably simple matter to determine with considerable confidence either the maximum or minimum rainfall that may be expected in a given length of time.

MR. CARL P. BIRKINBINE: The curtailment of this paper into a short presentation necessitated the omission of many statements. The thought intended was that the Ohio Valley rainfall in March, 1913, was the greatest quantity of rain on so large an area of which we have any record in this part of the country. Prof. J. Warren

Smith of the Weather Bureau in a paper on this flood said, "When the extent of the territory involved and the sequence of the storms is considered, no previous record exists which, in this section of the country, is in any way comparable with the rainfall of March 23–27, 1913."

The studies to which Mr. Longley refers should prove not only interesting but also of real value, especially as the precipitation records of but few stations extend back as much as fifty years. The obviation of damage by floods and the requisite storage reserves to maintain a supply during unusually low seasons are primary problems of water supply engineering. The occurrence of floods of various intensities in probable cycles has been recognized; but drought conditions generally leave no natural record, such as high water marks do of floods, and except where long time gauges have been maintained on streams, the data regarding these must be taken from precipitation records. Mr. X. H. Goodnough's recent discussion of a century of rainfall at New Bedford, Massachusetts, clearly showed the irregularity in intensity and occurrence of the periods of deficient precipitation, while other long time records can be plotted to indicate such facts. But any studies which will assist in making better scientific guesses at extreme conditions will benefit the profession, and hence the people served.

Many interesting facts and data regarding precipitation are buried in the files of engineering offices and scattered through records both public and private. It would be a gratification to the author if this paper would suggest more extensive publication, and perhaps later a systematic collection of the occasions and variations in precipitation. As Mr. Provost pointed out engineers should endeavor to obtain governmental publication of data in more useful form than at present, and as water works engineers and superintendents form a large proportion of the high grade coöperative observers, we can anticipate a closer harmony of operation with greater mutual exchange of data between the National Bureau and the profession.

Mr. Sidney K. Clapp: The paper by Carl P. Birkinbine is of extreme interest and represents an immense amount of research and compilation of very important data. It is so exhaustive that it seems unnecessary to discuss it in any detail. It may be interesting, however, to add a few words in relation to experiences in the

Catskill Mountain region, where some careful records have been kept for about thirteen years.

Attention may be drawn to the paper recently published by the New England Water Works Association, September, 1915, in which Mr. X. H. Goodnough has given many interesting and additional facts relative to New England rainfall. The conclusions reached in the above-noted paper and the subsequent discussion could only be repeated in this instance, and the discussion by Mr. George G. Honness covers practically all the work of the board of water supply in the Catskill region of New York.

There is no doubt that mountain condensation is a very important factor in runoff and is not often included in rainfall, although it may be very great and no doubt explains in part many high percentages of rainfall. Another important factor, not considered as often as it should be, is the question of evaporation and few, if any, new ideas have recently been proven, and it still remains a somewhat unknown quantity, although very important in many cases. That the personal equation enters into the results obtained is no secret, and results are often secured which need some explanation before being accepted. The difference in location of gauge, even in the same general neighborhood, acts in a very peculiar manner and care should be taken to determine all these facts before accepting any peculiar results as a record.

Snow is a very important factor in rainfall and the methods of obtaining the "equivalent rainfall" will bear inspection, and modify results in many instances. That it is important is shown on a very interesting view, taken March 2, 1914, showing sagging and broken telephone wires encrusted with ice and snow three inches in diameter.

Thunderstorms seem to be of local origin and vary in intensity in very limited areas, especially in the mountain regions. The results of these showers, combined with the ordinary rainfall data give very distorted figures which are sometimes misleading if taken for a short period.

Mr. Frederick J. Rehn, Assistant Engineer, Board of Water Supply of the City of New York, has compiled some very interesting figures in relation to influence of altitude on rainfall in the Catskill Mountains of New York, which are hereto appended.


Res. 1293
3/2/14

ALTITUDE INFLUENCE ON RAINFALL IN THE CATSKILLS

The location and distribution of rain gauges in the Catskill watersheds were made with a view to obtain the best average for each catchment area. The range of elevation is from 190 feet at Kingston to 2300 feet at Peekamoose. During the summer months Overlook Mountain gauge has an elevation of 3000 feet. On account of inaccessibility, during the winter season the gauge is located on the southerly slope towards Woodstock at an elevation of 900 feet. Due to the difficulty of obtaining a continuous record at very high altitudes, no extensive experiments have been had for the study of variations of rainfall and snowfall due to differences of elevations.

TABLE 1

Catskill watersheds rainfall. 8-year averages (1906–1913)

MARK	STATION	ELEVATION	RAINFALL	
BS	Brown Station	540	45.96	
Cl	Claryville	1750	47.57	
C	Cornwall	200		
Ed	Edgewood	1900	48.36	
Fn	Franklinton	1175	32.08	(7 yr. mean)
G	Grahamsville	900	44.80	
HaF	Haines Falls	1910	45.44	(7 yr. mean)
HiF	High Falls	200		
Hi	Highmount	1900	39.60	
HJ	Hopewell Jct	300		
K	Kingston	190	41.06	(7 yr. mean)
L	Lackawack	700	42.70	
LH	Lake Hill	1200	47.04	
Lx	Lexington	1440	36.93	
Mo	Moonhaw	1200	58.96	
NP	New Paltz	200		
OH	Oak Hill	700	34.51	(7 yr. mean)
OMt	Overlook Mt	3000	47.46	
Pk	Peekamoose	2300	58.33	
Pa	Phoenicia	750	46.58	
PV	Pleasant Valley	220		
Pr	Prattsville	1165	33.80	(7 yr. mean)
PH	Preston Hollow	850	33.28	(7 yr. mean)
S	Silvernails	380		
Sl	Slide Mt	1900	55.55	
Sn	Sundown	1000	44.63	
W	Walden	400		
Wo	Westerlo	1160	33.24	(7 yr. mean)
WH	West Hurley	565	44.25	(7 yr. mean)
WS	West Shokan	540	48.49	
Wm	Windham	1500	35.61	(6 yr. mean)

In the summer of 1907 two gauges were installed at practically the same location, one at Edgewood in the Esopus watershed at an elevation of 1900 feet, the other on top of Hunter Mountain at an elevation of 4000 feet. Synchronous records were kept for a period of 34 months, which gave a rainfall 5 per cent higher for the Hunter Mountain gauge. The style of gauge used at both stations was the standard Friez 8-inch United States Weather Bureau Gauge.

Isohyetal maps of the Catskill watersheds for the year 1913 and a composite map for the years 1906 to 1913 inclusive, show better than any wordy comparison the general effect of altitude on the distribution of rainfall. These maps show a well defined summit of rainfall corresponding to the mountain elevation summits forming the divide between the Esopus and Rondout watersheds, with a maximum fall of 60 inches in 1913. The influence of the divide between the Esopus and Schoharie watersheds also is very marked. Here Hunter Mountain and Overlook make their presence felt.

For the 8-year mean, 1906–1913 inclusive, the greatest difference in rainfall between two stations was 19 inches: Peekamoose, elevation 2300 feet, gave 58.33 inches; Highmount, elevation 1900 feet, gave 39.60 inches. Slide Mountain, elevation 900 feet, gave 55.55 inches; West Hurley, elevation 565 feet, gave 44.25 inches; Kingston, elevation 190 feet, gave 41.06 inches.

Table 1 gives list of rainfall stations, Catskill watersheds, their elevations and some data of the 8-year record as kept by the board of water supply. These data will support the well known fact that mountains do materially affect the distribution of rainfall, but are not sufficient to reach any conclusion as to what the difference might be for varying heights. If local thunderstorms could be eliminated the data would be in better shape for comparison upon which to base a conclusion.

MR. JOHN C. TRAUTWINE, JR.: In view of the very exhaustive character of Mr. Birkinbine's paper, I submit that it should be entitled "A Treatise on Precipitation," and published in book form.

The author has covered his ground so fully as almost to preclude discussion respecting the subject proper; but I venture to mention two related matters discussed by the author near the close of his paper, viz., the appearance of tidal phenomena in inland waters, and the effect of deforestation upon precipitation and upon runoff.

Engineering News recently described a case where the waters of a lake, not far from a tidal sea, underwent daily changes of level, corresponding, at least in a general way, with those of the neighboring tidal water; and the suggestion was offered that the daily (and apparently tidal) fluctuations of the lake surface might be accounted for by hypothesizing the presence of an impervious and flexible stratum (as a clay bed) between the two waters, said stratum transmitting the pressure changes, due to ebb and flow, from the sea to the inland water, much as an india rubber diaphragm might do.

The speaker's impression has been that the old time faith in the effect of deforestation upon rainfall has been seriously undermined by recorded facts, and that a prominent official of the Weather Bureau recently denied the effect of deforestation even upon runoff.

MR. CARL P. BIRKINBINE: Replying to Mr. Trautwine's discussion; the variations in inland lakes referred to in the paper were those due to climatic conditions and the resultant irregularities of precipitation. The present Great Salt Lake and the Otero soda basin are the most striking examples in this country of the desiccation of large bodies of water, while other instances have been studied in Europe and Asia. The fluctuation in lake levels within relatively few years was related to climatic conditions by Brückner, and later investigations have contributed much along the same lines. Dr. Huntington found a close relation between the levels of Owens Lake in California and the growth of adjacent trees.

As to the matter of precipitation and runoff being affected by deforestation and agricultural development, the point brought out in regard to precipitation includes two separate ideas. One that the different temperature conditions between forest and open land may alter the character of the precipitation, that is from rain to snow or vice versa. In this connection there has recently been published a paper claiming a different depth of snow fall for forested areas from that for open ground; although as the effects of ground temperature, ground moisture and wind are to be considered, the conclusions of the paper are not yet definite. It has also been claimed that land under cultivation permits higher evaporation from the soil, thus extending the area of condensation, although this would need to cover a large area to be appreciable.

It is true that a former high official of the Weather Bureau strongly stated that deforestation did not affect the runoff, but I do not accept this as a general statement. Records of stream flow both maximum and minimum, the visible signs of erosion on bare ground, the slow melting of snow in shaded areas, the reduction of intensity offered by leaves and branches during severe downpours, the greater porosity of forest humus and the fact that it does not freeze deep, and the more uneven and obstructed floor of the forest as compared to bare hill or field, cannot fail to have the effect of stabilizing runoff, and this view is generally shared by those who have studied the records and conditions, especially in this country where deforestation generally clears the ground of all growth.

Mr. Nicholas S. Hill, Jr.: In the preparation of this paper Mr. Birkinbine has confined himself quite closely to the first half of his subject as set forth in the title. That is, he has treated very fully the subject "Variations in Precipitation" and touched rather lightly upon their "Effect Upon Water Works Engineering." In this he has been actuated by a desire to be brief. Under the circumstances, the writer deems it proper that the second half of the subject should be brought out somewhat more fully in the discussion. He will, therefore, confine himself largely to a discussion of this phase of the subject, and the more especially so as Mr. Birkinbine's comprehensive treatment of the "Variations in Precipitation" leaves comparatively little to be said upon this subject by way of criticism, amplification, or comment.

Studies of hydrologic and meteorological phenomena, familiarity with laws governing their occurrence, so far as these are known, and an understanding of the nature and influence of the various conditions by which these phenomena are affected, are of great interest and value to the practicing engineer.

To the civil, hydraulic and sanitary engineer a thorough understanding of these phenomena, with particular reference to the causes, extent, mode of occurrence, distribution and variations in precipitation, in the territory in which he practices his profession, is indispensable.

His interest extends to nearly every phase of this branch of the science of meteorology. The extent, mode of occurrence, seasonable distribution, and variations in precipitation are of direct interest to him in many ways. Torrential rains erode embankments and the slopes of cuts unless these have been designed to withstand their action. In areas in which such rains occur, particularly if they may be accompanied by high winds, the walls of masonry buildings must be more substantially constructed, and more thoroughly waterproofed to enable them to resist the penetration of moisture, than would be the case elsewhere. Heavy snowfalls impose considerable loads upon roofs, which must be designed to resist safely the maximum stresses which may result from this cause. Snowdrifts may seriously impede the operation of steam and electric railways unless suitable snow brakes are designed and installed. In some localities hail storms may occur, of sufficient intensity and frequency to justify the engineer in incorporating in his designs special provisions for resisting their damaging effects. Severe

storms of wet snow and sleet will exert an influence upon the design of many engineering structures, particularly upon overhead wiring systems, and exposed mechanisms, and devices of all kinds. Even the occurrence of protracted dry spells may influence the drafting of engineering specifications and lead to the introduction of clauses requiring that concrete be wet at intervals following the removal of forms, and that brick be well moistened before being laid.

The above are only a few of the many direct ways in which the precipitation characteristics of a territory may exert an influence upon design.

In many of the drainage problems, the engineer's interest in the amount, time and mode of occurrence, and particularly in the probable intensity of precipitation during a moderate interval, is hardly less direct than in the cases above mentioned. The required capacity of storm water sewers, culverts and drains at any point depends upon the maximum volumes of surface runoff which may reach that point simultaneously. With any given tributary area, that is, with an area, the size, shape, soil character and topographical features of which are fixed, this total volume will depend directly upon the most severe conditions which may occur as regards precipitation. In cases of this kind, records of intense storms, of which Mr. Birkinbine presents a considerable number, are of great value, and usually form the only basis for computing intelligently the maximum runoffs and the required capacity of the structure. Where past experience is the only guide to the future, it is important that this experience be recorded, and the records be easy of access. The duration of storms of varying intensity is also of prime importance. If the catchment area is of very limited extent, as, for example, a roof, the maximum recorded precipitation for a one or two minute interval may impose a more severe tax upon the capacity of the drains than would the maximum recorded precipitation for a fifteen or a thirty minute interval. With the larger area tributary to a culvert or catchment basin, the reverse will be true, for in this case, with very intense precipitation during short intervals, the depositions in the immediate vicinity of the culvert or basin pass off before the arrival of equally intense precipitation from parts more remote, and these, upon reaching the culvert or drain, are combined with later and less intense depositions upon areas nearby. The critical period of intense precipitation, i.e,, the period during which the maximum precipitation will control the design,

varies with the physical features of the area drained and must be determined for each case. The value of data recording intense storms of varying duration is, therefore, apparent. The engineer may also be obliged to consider whether or not an intense storm may occur when the ground is still frozen, thus contributing to a high per cent of runoff, and whether its occurrence coincidentally with melting snows from earlier depositions is sufficiently probable to warrant being taken into account. In all such questions past records, if of long duration, form the best guide.

In addition to instances already mentioned, there is a very important group of problems in which the engineer's interest in precipitation phenomena, though indirect, is very keen. Reference is here made to that large class of problems involving the yield of surface and underground catchment areas and the design of works looking to its utilization and control. Here the interest of the engineer is primarily in questions of runoff and percolation, of the amount and variations in the probable yield of the surface and underground sources of supply rather than in the amount and variations in precipitation. He is interested in the rainfall only because it is the source and cause of the yield.

The problems falling within this group may be divided broadly into three classes:

(a) Those in which the probable maximum hourly, daily, weekly or monthly runoff must be known;

(b) Those in which the probable minimum daily runoff is of importance, and

(c) Those in which the average daily yield by months, consecutively, or in chronological order, for a long period, of, say forty years, is desired.

Class (a) embraces problems of dam design, the proportioning of spillways and waste way channels, the protection of structures against floods, flood prevention, the regulation and control of the regimen of streams, the design of storm water sewers and drains, and the like.

Class (b) may be instanced by the problem of the disposal of sewage and sewage effluents by dilution in inland waters.

Class (c) embraces those hydrologic problems connected with water supply, hydraulic power development and irrigation which involve determination of the average, and safe, or minimum, yield of surface and underground catchment areas with various amounts

of storage, the storage required to produce a desired yield, and the like.

The problems of class (a) are very similar to the drainage problem previously referred to, except that the conditions are here far more complex because of the size, and of the variable topographical and geological characteristics of the catchment area considered.

Although Mr. Birkinbine has mentioned many notable exceptions, the heavy floods in north temperate regions frequently occur in the spring of the year, when the soil is saturated by the precipitation of the preceding fall and winter, the partly frozen ground is favorable to a high percentage of runoff, and melting snow and ice contribute largely to its volume. Under these circumstances it is readily seen that the runoff in which the engineer is primarily interested will bear a very indefinite relation to the cotemporaneous precipitation, and anything approaching accuracy in the estimation, from precipitation records alone, of the probable maximum flood flow on a given catchment area will prove impossible.

Similar difficulty is experienced in attempting to estimate the probable minimum runoff, from precipitation records alone. On some sheds of considerable size the stream flow may entirely cease for several consecutive weeks. Another shed not many miles distant may exhibit a well sustained, or even heavy, dry weather flow under practically identical conditions of rainfall. Topographical and geological conditions on the watershed exert an important influence on the minimum runoff to be anticipated therefrom. The runoff from small flashy sheds having steep slopes, sparsely wooded, with limited ground water storage, and unaffected by springs, will respond well to variations in precipitation. Other sheds nearby may have moderate slopes, porous soil and considerable wooded areas. The soil of these areas may be blanketed with leaf mold, which absorbs the moisture of heavy rains like a sponge, and, being well shaded by deciduous trees with a resulting low evaporation, may have the effect of a storage reservoir. Such a shed will show a lower maximum and a much higher minimum runoff than will a flashy shed under the same conditions of rainfall. The presence of springs, too, may exert a very marked influence in sustaining the dry weather flow, and this is a factor for which it is practically impossible to apply a reasonably accurate correction without actual gaugings.

A study of the following tables will be illuminating as regards the marked differences in runoff per square mile which may occur

on watersheds in the same section of the country under closely similar conditions of precipitation.

The geographical centers of the two Pennsylvania sheds in table 1 are only 25 miles apart; and of the two New York sheds about 60 miles apart. The Pennsylvania sheds are about 125 miles distant from the New York sheds.

The very high yield of the Little Lehigh has been determined, from personal study and inspection of the shed, to be largely attributable to springs, which also affect the flow of the Pohopoco, but to a lesser extent. Observe that whereas in a month of low rainfall the per cent of runoff to rainfall on the Esopus is one-seventh less than on the Croton, the average per cent of runoff to rainfall during the seven years, 1906 to 1912, is one-third greater on the Esopus than on the Croton. The high average annual percentage yield of the Esopus as compared with the Croton is not attributable to any single cause, and was, in fact, not fully anticipated by the eminent engineers who studied this shed prior to its selection as the source of a supplementary supply for New York City.

TABLE 1

Differences in runoff per square mile, during a dry month on nearby watersheds under closely similar conditions of precipitation

(1) NAME OF WATERSHED	(2) AREA SQUARE MILES	PRECIPITATION SEPTEMBER, 1914		(5) NATURAL AVERAGE RUNOFF IN THOUSAND GALLONS DAILY PER SQUARE MILE SEPT., 1914	(6) PER CENT OF SEPTEMBER RUNOFF TO SEPTEMBER RAINFALL
		(3) Inches in depth	(4) Thousand gallons daily per square mile		
					per cent
Croton River at New Croton Dam, New York	360.4	0.32	183	95	51.9
Esopus Creek between Ashokan Dam and Glenerie, New York	172.5	0.56	322	142	44.1
Pohopoco Creek near Mauch Chunk, Pa.	110.0	0.50*	290	260	89.6
Little Lehigh near Allentown, Pa.	98.0	0.28†	162	581	358.6

* United States Weather Bureau Statistics, East Mauch Chunk, Pa. = basis.
† United States Weather Bureau Statistics, Allentown, Pa., = basis.

If large difficulties attend the estimation, from precipitation records alone, of the probable maximum and minimum runoff or yield of a given catchment area, these difficulties sink into insignificance compared with those which arise when, as in the problems of class (c), the data desired are chronological records of runoff, consecutively by months, over periods sufficiently long to embrace all probable extremes of flood and drought. That this must inevitably be true is apparent at once from a mere statement of the complex relationship subsisting between precipitation; evaporation, including transpiration; percolation, and stream flow.

The immediate source of every supply of fresh water, whether surface or underground, is the precipitation upon the surface or underground catchment area tributary thereto. The ultimate source is, of course, the sea. The phenomenon of precipitation may be briefly described as follows, evaporation of water, through the agency of the sun's heat, into aqueous vapor; transportation by winds of clouds so formed; condensation resulting from lowered temperature, and precipitation.

This statement of the phenomenon suggests that, other things being equal, the following factors contribute to high precipitation:

1. Nearness to the source, that is, to the sea, or other large body of water.

2. Geographical position in the path of prevailing winds from the direction of the source.

3. Position in the average track of climatological disturbances, barometric depressions, or storms.

4. Position with respect to prominent topographical features, such as mountain ranges, particularly those running at right angles to the direction of the rain bearing winds, and which contribute to a lowering of temperature, and hence to condensation and precipitation.

Of the precipitation deposited upon the earth, part runs off directly into the streams and augments their volume of flow. The percentage of the total deposition which thus runs off directly varies with the form and intensity of the precipitation, the steepness of the slopes on which it falls, the composition of the soil as regards porosity and its condition as regards freezing, the surficial condition of the catchment area as regards snow, vegetation and other elements which may accelerate or retard the precipitation in its course toward the streams.

Part is reconverted into aqueous vapor by evaporation from water or land surfaces, or by transpiration from forests and vegetal coverings of all kinds. The percentage of the total deposition thus lost varies with the form and intensity of the precipitation, with the temperature, with wind velocities, with relative vapor pressures, with the extent of water surface, extent and character of vegetation, season of the year, degree of saturation of the soil, and so on.

Part percolates into the ground. The percentage of the total deposition which is thus temporarily or permanently withheld from the stream varies with the porosity of the soil, with its slope and surficial condition, its condition as regards freezing and with its degree of saturation.

Of the portion which percolates into the ground, a large part eventually reappears in the streams, sustaining their flow during the months and years of low precipitation. The amount by which the stream flow is thus augmented varies with the composition of the soil as to porosity, its condition as regards freezing, and the state of depletion of the ground water storage.

The runoff in a given month may considerably exceed the total precipitation on the catchment area during that month. In another year the runoff for the same calendar month may be very much less than the corresponding precipitation. For the same annual rainfall, the annual runoff occasionally varies by nearly 100 per cent on the same stream.

A layman might infer from the foregoing remarks that runoff, after all, bears a very indefinite relation to cotemporaneous rainfall, and, therefore, that a knowledge of the amount of, and variations in, precipitation is of slight use as a means of judging the probable amount of, and variations in, runoff. This is not the case. Notwithstanding the extreme complexity of the relationship between precipitation and runoff, they do bear to each other the definite relationship of cause and effect. The relatively large number of precipitation records of considerable duration, as compared with the fragmentary and brief runoff records usually available, has led to a number of ingenious and able attempts to express this relationship by means of formulae.

The most recent of these efforts is fully described in a valuable 100 page paper entitled "Computing Runoff from Rainfall and Other Data" presented before the American Society of Civil Engineers on April 21, 1915. The paper is by Adolph F. Meyer,

M. Am. Soc. C. E. A similar attempt was made twenty years ago by C. C. Vermeule, then Topographer and Consulting Engineer of the Geological Survey of New Jersey, and the results published in his "Report on Water Supply, Water Power, the Flow of Streams, and Attendant Phenomena," forming Vol. III of the Final Report of the State Geologist, 1894. Messrs. Justin,[1] Babb,[2] Rafter,[3] Newell,[4] and others have also made investigations along these lines.

Such formulae do not form a reliable means of building up a chronological monthly record of runoff from precipitation records alone. Their employment is strictly limited to sheds for which long and accurate monthly meteorological records of precipitation, temperature, etc., are available. Except through the use of arbitrary coefficients to be assumed by the computer they do not provide corrections for characteristic differences in the topographical configuration and shape of the drainage area, geological formation, vegetal covering, springs, etc., any or all of which may exert a marked influence upon the relationship which the formulae aim to express. They are of more value in cases where a long and reliable meteorological record exists in conjunction with a fragmentary or brief runoff record. Under these circumstances the runoff computed with tentative coefficients may be compared with the corresponding actual runoff where known, and the first assumption as to the proper water shed coefficients modified in the light of this comparison. As a rule, their authors do not make extravagant claims as to the usefulness of formulae of this kind. Mr. Meyer has this to say with regard to his own results:

Let it be understood at the outset, that the writer does not claim to have discovered a method of computing daily or even monthly runoff from rainfall and other physical data which obviates the necessity for stream measurements. He believes, however, that he has found a method of computing the annual runoff from widely different watersheds with considerable accuracy, and of computing a reasonable distribution of such runoff through the various months of the year for most of such watersheds.

With regard to the efforts of his predecessors, he says:

Although recognizing the able manner in which the subject of stream flow has been discussed in the technical press during past years, the writer cannot

[1] Transactions Am. Soc. C. E., vol. lxxvii, p. 346.
[2] Transactions Am. Soc. C. E., vol. xxviii, p. 323.
[3] Water Supply and Irrigation, Paper No. 80, U. S. Geological Survey.
[4] Fourteenth Annual Report, Part 2, 1892–1893, U. S. Geological Survey.

refrain from expressing the belief that the relations between rainfall and runoff indicated by the curves and formulæ just referred to, are, in a varying degree, generalizations, which bring out class likenesses, but obscure the individual characteristics of runoff from different sheds resulting from differences in the character and distribution of the rainfall, and the effect of temperature, vegetal cover, topography, soil and subsoil on the disposal of rainfall.

In the North Atlantic States resort is seldom had to methods of computing runoff from rainfall by formula. Engineers in the East are fortunate in the possession of five records of cotemporaneous rainfall and runoff, some of which approach the ideal as closely as can be expected with streams, the natural regimen of which has been altered by artificial storage. These records have been maintained for many years by the water departments of Boston, New York and Philadelphia. Reference is made to the Sudbury, supplying Boston, drainage area 75.2 square miles with precipitation and runoff records for forty years from 1875 to date; to the Croton, supplying New York City, drainage area 360.4 square miles with precipitation and runoff records for forty-seven years from 1868 to date; to the Tohickon, supplying Philadelphia, drainage area 102.2 square miles with precipitation and runoff records for twenty-nine years from September 13, 1883, to December 31, 1912; to the Neshaminy, supplying Philadelphia, drainage area 139.3 square miles with precipitation and runoff records for twenty-eight years from June 10, 1884, to December 31, 1912; and to the Perkiomen, supplying Philadelphia, drainage area 152 square miles with precipitation and runoff records for twenty-eight years from August 20, 1884, to December 31, 1912.

In this locality the usual practice is to adopt one of these long continued records of monthly runoff as a standard or base record, in the actual solution of problems of storage and of average and safe yield. Such fragmentary records of rainfall and runoff as may exist on the local shed under consideration are then used as a guide to the judgment in the selection of corrective factors to apply to these standard records to adapt them to local conditions as regards precipitation, and as regards such characteristic peculiarities of the local drainage areas as may influence the amount and variations of runoff. For this purpose the fragmentary local records are invaluable.

In general, it may be said that the ideal data with which to attack problems involving estimates of the maximum, minimum, average,

or safe yield of surface or underground sources of supply; the number of horse power hours available on water during an average year; the effect of storage on each of the above, and the like, are as follows:

(a) Continuous records of monthly precipitation at a number of representative points on the watershed for a period of forty years.

(b) Continuous records of natural average daily runoff per square mile of watershed by months for a cotemporaneous period of forty years.

A forty year period is mentioned because experience indicates that it takes thirty to forty years to secure an accurate measure of the mean annual rainfall at any given place. Such a record is likely to include all extremes of flood and drought which may occur, and it

TABLE 2

Differences in average annual runoff per square mile, during seven consecutive years, on nearby water sheds under practically identical conditions of precipitation

(1) NAME OF WATERSHED	(2) AREA SQUARE MILES	(3) PERIOD CONSIDERED	(4) AVERAGE ANNUAL PRECIPITATION		(5) AVERAGE ANNUAL RUNOFF IN THOUSAND GALLONS DAILY PER SQUARE MILE	(6) PER CENT OF RUNOFF TO RAINFALL
			Inches in depth	Thousand gallons daily per square inch		
						per cent
Croton River at New Croton Dam, N. Y....	360.4	1906–1912	47.99	2285	10.70	46.8
Esopus Creek at Ashokan Dam..............	255.0	1906–1912	47.99	2282	14.15	62.0

is reasonable to conclude that, to secure the true means and extremes of runoff, a record of similar length must be available.

The above facts so far as they relate to rainfall are well exemplified in table 2 of Mr. Birkinbine's paper, from which it is seen that the averages of precipitation at Philadelphia during the forty-four years from 1871 to 1914 compare extremely well month by month with the corresponding averages for the entire ninety-four year period of record. Needless to say, such complete data are never found on streams the development or utilization of which is proposed.

In his paper entitled "Computing Runoff from Rainfall and Other Data," to which reference has already been made, Mr. Meyer states: "Precipitation and temperature are being observed in the United

States at more than 5000 stations. Stream measurements are being made by federal and state authorities, and private parties, together, at about one-fourth as many stations." Thus there is in the United States at the present time about one rain gauging station for every 600 square miles of territory and one stream gauging station for every 2400 square miles. The runoff records are for the most part of short duration.

Not long ago the writer was called upon to estimate the safe yield of a watershed 110 miles in extent in one of the most densely populated of the original thirteen states. There was no point on the shed at which precipitation records had ever been maintained, and although two water companies and one power user of considerable size had obtained their supplies from this stream for many years, no flow measurements of any kind were available. Such cases are by no means uncommon.

The precipitation records which exist are for the most part reliable and many of them cover periods of considerable length. Mr. Birkinbine notes ten places, Boston, Albany, Providence, Philadelphia, Charleston, New Orleans, Cincinnati, St. Louis, Fort Leavenworth and St. Paul, at which records are available for periods of from seventy-five to one hundred years. All of them are continuous except that at New Orleans which is broken from 1860 to 1868. To these may be added:

	years
New Bedford, Mass	100
Waltham, Mass	90
Lowell, Mass	88
Rochester, N. Y	86
New York City, N. Y	79
Amherst, Mass	78
Worcester, Mass	74
Cambridge, Mass	74
Newark, N. J	72

According to Mr. X. H. Goodnough, Chief Engineer, Massachusetts State Board of Health, reliable precipitation records in New England date back to 1749. (See exhaustive paper entitled "Rainfall in New England" in *Journal of New England Water Works Association* for September, 1915.) Those at Charleston, S. C., date back to 1737. Records exceeding forty years in length are quite numerous throughout the United States. It is seldom, however, that more than one such record will be found on or near watersheds of moderate extent.

Attention should be drawn to the fact that large errors may result from applying the district normal to individual watersheds, or from assuming that a single record on or near a drainage area is representative of the average precipitation on the shed as a whole. This holds true even for sheds of limited size. On Esopus Creek above Ashokan Dam with a drainage area of 255 square miles, the recorded rainfall at the Moonhaw Lodge gauging station of the Board of Water Supply of the City of New York has been 50 per cent greater over a period of several years than at the Highmount Station located in the same shed and only a few miles away. At the time this stream was first talked of as a future source of supply for New York City, the nearest extensive precipitation record was that at Albany, 50 miles away. There was also a fragmentary record at Kingston, 12 miles below on the same stream, and a few records at three points, Windham, Griffins Corners and Mohonk Lake, lying just outside the border line of the shed. There was no rain gauging station on the shed itself at that time. The district normal for Albany and points on the Esopus watershed as read from the chart "Normal Annual Precipitation in the United States, 1870–1901," see plate 2 of Mr. Birkinbine's paper, is 40 inches. The actual average annual precipitation at Albany during the eighty-seven years from 1826 to 1912 was 38.15 inches. Subsequent to 1905 some ten rainfall gauging stations were established on the Esopus by the board of water supply. The average annual precipitation on the shed for the seven years 1906 to 1912 was 47.94 inches with a variation in the average as between stations of from 39.61 inches at the Highmount Station to 58.63 inches at the Moonhaw Lodge Station. The average of all stations (47.94 inches) for this period of seven years was, therefore, 20 per cent higher than the district norm. At Albany during these same seven years the average annual precipitation was only 30.75 inches or 23 per cent lower than the district norm. At the three points lying just outside the border line of the Esopus shed, Windham, Griffins Corners and Mohonk Lake, the average for the seven years was 40.61 inches, and at Kingston for the six years 1907 to 1912 it was 41.19 inches, or just a little above the district norm. There is no doubt whatever that the application to the Esopus water shed, in unmodified form, of the district normal, of the long Albany record, of the fragmentary Kingston record, or of values obtained at the three gauging stations near the border line of the shed would have produced an estimate of precipitation 20 per cent to 40 per cent below the true values for this shed.

The case illustrates well the desirability of long records well distributed over the drainage area under investigation. Under these conditions data obtained at gauging points on each of the principal branches of the main stream may be grouped and averaged, and the results weighted according to the extent of the subareas to which they apply. It must not be inferred, however, that such records are indispensable to the drawing of reasonably accurate conclusions as to the average amount of precipitation to be expected on a given shed. Many of the variations in precipitation as between points on and near the Esopus watershed are understandable and to have been anticipated in the light of the known laws affecting the occurrence of precipitation phenomena. To the extent that this is true the case emphasizes, rather, the importance of a thorough knowledge of these laws on the part of those who have occasion to utilize such records.

As has been previously stated, runoff records in the United States are for the most part fragmentary and of short duration. Those which exist are less accurate than precipitation records, though, of course, more dependable than runoff estimated from the precipitation. The greater part of these records are obtained by gauging the flow of streams at selected points by means of a current meter. Measurements are made at different stages of the stream from low flow to high water, and a rating curve prepared. With this curve established the subsequent discharge may be estimated from the stage of water in the stream which is usually observed once or twice daily. Aside from the sources of error inherent in the method one or two others may be noted:

(a) The method aims to give the daily quantity of water passing a given point. To be useful this must, ordinarily, be reduced to terms of runoff per square mile of watershed per day. In districts which have been mapped out by State or Federal geological surveys, the total drainage area above the gauging station may readily be ascertained. But on many streams considerable quantities of water, of variable and unknown amount, are abstracted above the point of gauging and devoted to irrigation and water supply uses. Frequently, too, there are water power developments on these streams which, while they do not actually abstract any considerable volumes of water, greatly change the regimen of the stream through pondage. A ten hour power with small pondage would be likely at some seasons to draw fully upon this pondage during the ten working hours, thus sending down abnormally large quantities of water at the very times during which the stage of the stream at the gauging point was being observed. If the pondage were large it might, and probably would, be operated in such a way as still further to vitiate the natural flow of

the stream below the power site. It is manifestly impossible for the government bureaus in charge to apply proper corrections in cases of this kind, and it is equally impossible for the engineer who has occasion to use their published data to do so.

(b) The rating curve mentioned above is determined under and applies only to open water conditions. In northern latitudes, streams may be frozen over for several months of the year. To determine with reasonable accuracy the daily discharge of a stream under ice conditions, frequent gaugings by current meter are required. This is often difficult because of the formation of needle ice. It is always expensive, usually prohibitively so. Thus the reported discharge during the winter months may be quite undependable.

(c) In some cases, the flows at high stage can be estimated only roughly because of the stream overflowing its banks, or for other reasons.

The official runoff records of so important a stream as Esopus Creek afford examples of all three of the sources of error mentioned above, and the possibility of their existence must be recognized and allowed for in utilizing these records in conjunction with those of precipitation.

Speaking generally of Mr. Birkinbine's paper, it may be said that he has treated his subject, especially that part of it which deals with "Variations in Precipitation," in a very comprehensive and able manner, and in so doing has performed a valuable service. In the view of the writer, if the paper is open to adverse criticism in any respect, it is upon counts so minor as to be unworthy of mention.

Mr. Carl P. Birkinbine: Mr. Hill's able article is welcomed, and he has correctly surmised the basic idea of the compilation of the paper. The desire was to keep its length within proper bounds and refer to the important and intimate relation between precipitation and water works engineering; and by references and data on the former subject, supplemented by brief comment upon the interrelationship, to bring out more detailed discussions of some of the many phases of hydraulic as well as general engineering, which are to be studied in connection with precipitation conditions.

Mr. Hill has emphasized the value and necessity of familiarity with hydrologic and meteorological phenomena, and urges the accessibility of important records. The reference to drought conditions demanding greater precautions during construction of cement and brick work, suggests other mention of the direct or resultant effects of precipitation conditions upon engineering constructions. Such are: coffer dam building, excavation of wet or sun baked earth, flooding of open cuts by direct rainfall or percolated water, seepage into tunnels and shafts, earth slips and slides of satu-

rated soil, quicksand troubles, expansion or shrinkage of timber and ropes, hauling on wet earth roads, ice coatings on materials and roadways, heating of large pipes by sunshine, shorter number of daylight hours because of various storm conditions, reduced working time and efficiency of workmen in rainy periods, etc.

The occurrence of heavy floods in the spring in the north temperate region is, for some streams, almost annual, and this is predominently the season of maximum high water. The references in the paper to maximum floods occurring because of rainfall alone were inserted to emphasize the fact that the spring runoff may be exceeded by that due to heavy summer rains on the watershed or to severe and successive thunderstorms on a small area. The first type of occurrence produces high runoff by soil saturation, while the second form often creates a quick and heavy surface discharge because of the hard condition of the ground and the excessive deposition in a period of short duration.

Tables 1 and 2 of Mr. Hill's discussion present interesting data, especially when studied with the detailed facts. In table 1 the wide range between Pohopoco Creek and the Little Lehigh watershed, caused by the flow of springs, is, to quote Mr. Hill, "one of the best examples as to how underground water conditions may change computations based on rainfall records."

The discussion of the complex relation between rainfall and runoff was purposely omitted from the paper to keep down its length, but Mr. Hill's clear and brief discussion of this, which may be summed up in his sentence, "That they bear to each other a definite relation to cause and effect," is valuable.

The relative accuracy of periods of different lengths have been shown by tables and curves, compiled by various authors; but in using such averages it is important to know the conditions of irregular periodic variations which occurred in the interval; for a period of several decades may include or just miss a cycle of great or small precipitation whose duration is more than one-third of the total period.

Mr. Hill has shown by specific examples the desirability of long records well distributed over the area, and how variations between stations are explainable. The late Emil Kuichling, in a private discussion, forcibly expressed his disapproval of the unsystematic location of rain gauges in the United States, and advocated having these placed at the corners of areas 20 miles square covering the

entire country. The writer does not concur in such a rigid location because of topographic and natural conditions and meteorological phenomena, but points out that the present stations in the United States, being both official and coöperative, are not balanced with respect to area, altitude, wind direction, storm paths, proximity to water surfaces and mountain ranges, latitude, etc. Many important data are obtainable from the few localities which maintain several gauges in proximity, especially when, as at Philadelphia and New Orleans, these recorded intensities during the various intervals of precipitation, and more of such gauges are also desirable. Only time can add to the present small number of extended records, but engineers can urge and often contribute to the location and operation of new gauges so placed as to add to available data. The government records of stream flow, precipitation and other meteorological conditions have contributed largely to many important engineering studies. The engineering associations would be warranted in urging in unison larger appropriations from state and federal governments for this work, because the engineer works for the good of the people; and their sincerity will be emphasized by individual efforts to maintain coöperative stations and give the data collected to the Weather Bureau, which would gladly publish it for the benefit of all.

The author appreciates the interest in the subject matter shown by the various contributors to the discussion, and feels that their careful analyses of the paper and the additional information supplied by them will be of great value to those interested in the subject.

Mr. Ellsworth Huntington (by letter): Mr. Birkinbine's admirable paper brings out one point with special clearness. The most serious disasters arise from failure to prepare for extremes greater than have hitherto been recorded. The longer the meteorological record the greater the extremes which it shows. This is almost universally true, but in most places accurate records have been kept only about half a century or less. Will it continue to be true as the length of the records becomes greater? Suppose that we know what has occurred in a given region as to rainfall, floods, droughts, high winds and other climatic elements for a hundred years. If the margin of safety is based on records of such length, are we certain that our engineering works will stand any test that is likely to come to them?

The answer depends upon our conclusions as to climatic changes

in the past. Although exact numerical data are scanty, they suffice to show that there is a possibility that our water works, power-plants and other engineering projects may at any time be subjected to a strain greater than is indicated by the records of the past fifty or a hundred years. Let us take one special period, from the end of the thirteenth century, say about 1290 A.D., to the middle of the fourteenth, and see what happened then. At that time the level of the Caspian Sea rose with unparalleled rapidity. Previously the water had stood low enough so that a caravansérai was built on what is now the floor of the sea, at least 15 feet below the modern datum level. In the winter of 1306–1307 the water, after some years of rising, had reached a certain holy grave, well known even now, which is 37 feet above the datum level. That is, within a comparatively short period the level of this hugest of lakes rose at least 52 feet, the last part of the rise being very rapid. The natives, not perceiving any other cause, attributed the rise to the closing of a mythical underground outlet by earthquakes. The true cause was almost surely a sudden increase in rainfall.

If the Caspian Sea were the only line of evidence we might doubt this conclusion. Fortunately evidence from widely scattered parts of the world unites in showing that the period in question was a time of extraordinary climatic disturbance. For instance at Lop-Nor, an enclosed salt lake in the deserts of western China 2000 miles east of the Caspian Sea, a similar event took place. A Chinese chronicle relates that in the time of Chi-ta, who ruled from 1308 to 1311 A.D., the lake streamed over its banks, rising with great rapidity and overwhelming the Dragon Town of Lung-shong, which had formerly stood not far from its banks. Evidently we have here the same sort of catastrophe as at the Caspian Sea, but a few years later.

In Europe also this period was marked by unusual climatic stress. For instance, between 1296 and 1430 A.D., there occurred the four coldest winters on record in northwestern Europe. The facts are recorded in numerous old chronicles which have been studied by Norlind[1] and others. These documents state that in those winters the Baltic Sea froze to an extent unknown either before or since. The year 1296 was extraordinarily severe, but 1306 was worse, and 1323–24 was the severest winter ever known. In 1408 the Baltic

[1] A. Norlind, Einige Bemetkungen über das Klima der historischer Zeit.; Lunds Univ. Arsskrift. N. F. Afd. 1, and Vol. 10, No. 1. Lund 1914, 53 pp.

Sea froze again, but not so much as in 1323–24, when horses and sleighs crossed the ice from Germany to Sweden, an event never known in our day.

The conditions of the fourteenth century in northwestern Europe have been well summed up by Pettersson, Director of the Swedish Hydrographical Bureau. He says that the century presents

a record of extreme climatic variations. In cold winters the rivers Rhine, Danube, Thames, and Po were frozen for weeks or months. On these cold winters there followed violent floods, so that the rivers mentioned inundated their valleys. Such floods are recorded in 55 summers in the fourteenth century. There is of course, nothing astonishing in the fact that the inundations of the great rivers of Europe were more devastating 600 or 700 years ago than in our days, when the flow of the rivers has been regulated by canals, locks, etc., but still the inundations of the thirteenth and fourteenth centuries must have surpassed anything of the kind that has occurred since then. In 1342 the waters of the Rhine rose so high that they inundated the city of Mayence and the Cathedral "as far as a man's waist." The walls of Cologne were flooded so that they could be passed by boats in July. This occurred also in 1374 in the midst of the month of February, which is of course an unusual season for disasters of the kind. Again in other years the drought was so intense that the same rivers, the Danube, Rhine, and others, nearly dried up, and the Rhine could be forded at Cologne. This happened at least twice in the same century. There is one exceptional summer of such evil record that centuries afterward it was spoken of as "the old hot summer of 1357."[3]

Pettersson goes on to speak of two phenomena pertaining to the ocean as distinguished from the land. On these the old chroniclers lay great stress.

The first is the great storm-floods on the coasts of the North Sea and the Baltic, which occurred so frequently that not less than 19 floods of a destructiveness unparalleled in later times are recorded from the fourteenth century. The coast line of the North Sea was completely altered by these floods. Thus on January 16, 1300, half of the island of Heligoland and many other islands were engulfed by the sea. The same fate overtook the island of Borkum, torn into several islands by the storm-flood of January 16, which remoulded the Frisian Islands into their present shape. This flood is known as the "great man-drowning." On November 1, 1304, the island of Ruden was torn asunder from Ruden by the force of the waves. Time does not allow me to dwell upon individual disasters of this kind, but it will be well to note that of the nineteen great floods on record eighteen occurred in the cold season between the autumnal and vernal equinoxes.

[3] O. Pettersson: Climatic Variations in Historic and Prehistoric Times. Hydrographical-Biological Institute, Stockholm, 1914.

The other phenomenon to which Pettersson refers is the freezing of the Baltic Sea.

It will be noticed that the climatic extremes here described indicate that the winters were extraordinarily cold upon the lands, while storms of exceptional severity prevailed over the North Sea and occasionally penetrated inland. The summers on the continent were marked by storms of unprecedented severity alternating with intense droughts. In the North Sea region the summers must have been unusually wet. In England excessive moisture caused the crops to decline to such an extent that where in certain regions 12 bushels had been reaped on an average in the thirteenth century only 8 bushels were reaped in the period from about 1320 to 1350. In Norway similar disasters took place, and the crops declined so badly that the crown revenues sank 60–70 per cent. Far away in Greenland ice came down on the west and south coasts, and navigation was greatly impeded. Other disasters also took place, all apparently due to climatic severity. Thus the Norsemen seem to have been driven from Greenland.

In North America, as well as in Asia, Europe, and the great island of Greenland, there was a period of sudden climatic stress at this time. The curve of growth of the great Sequoia trees of California, as given in Mr. Birkinbine's figure 41, shows that between 1290 and 1350, A.D. the trees suddenly began to grow rapidly. So great and sudden a change in the rate of growth occurred at no other time in more than 2000 years, although still greater extremes may have prevailed at certain periods before the time of Christ. The nature of the climatic conditions in the fourteenth century may be judged in part from the strands of Owens Lake, which lies only 50 miles from the Big Trees. The lake and its tributary river have been measured and analysed with great care by the engineers in charge of the Los Angeles aqueduct. As the lake has now no outlet all the salt carried into it must remain until precipitated. The amount of sodium and chlorine is such that there is little likelihood that any appreciable amount has been precipitated. Analyses of the water from two-thirds of the lake's drainage basin show that the accumulation of the present amount of chlorine would require 4200 years and of the sodium 3500 years, the average being 3850. Since this applies to only a little more than two-thirds of the basin, the number of years must be reduced to about 2000. The fact that a larger supply of water would bring more salines

than are now being poured into the lake obliges us to reduce the figure still farther. Therefore we conclude that at the time of Christ or later, Owens Lake must have overflowed and been fresh. The old outlet is plainly visible at a height of 180 to 190 feet above the present variable level. Large beaches and rock-cut bluffs show that the water stood long at this high level. The climate must have been correspondingly more moist than at present. Below the outlet strand at Owens Lake there are several others. These correspond closely with the fluctuations of the growth of the Big Trees. Therefore it is possible to date them. The beach of the fourteenth century is so peculiar that even the layman notices it. It is larger, more pebbly, and more distinct than those above or below it. Such a beach could only have been formed when the lake was swept by unusually strong winds.

Thus from places as far removed as California, Greenland, Norway, England, the Rhine and Danube country, the Caspian Sea and western China, we find evidence that the fourteenth century was a time when the winds were stronger, the storms more severe, the rainfall heavier, and the occasional droughts more severe than at present. If such conditions should be repeated in our day, it is quite certain that many of our engineering works would be put to a test which they could not stand. Dams and revetments would be washed out, towns would be inundated, and buildings would be wrecked by the wind. In the intervals between such disasters the storage capacity of our reservoirs might prove inadequate, for the droughts of the fourteenth century appear to have been as extreme as the storms. If this sort of thing could suddenly take place 600 years ago, there is no assurance that it may not come upon us today.

In order to avoid the disasters which may at any time suddenly arise through a return to the conditions of the fourteenth century two methods are possible. One is greatly to increase the margin of safety in all our engineering works. This would be prohibitively expensive in view of the fact that we have no assurance that such a period of climatic stress is likely to come upon us. The other method is to find out the causes of climatic variability, and to devise methods whereby we may predict the general character of the seasons for months in advance. If we could know that floods, droughts, or exceptionally low temperature were likely to afflict a certain region, it would be comparatively easy to make such preparations. The prediction of such events is at present totally

beyond our capacity, but that does not prove that it will continue to be so. It is only about forty years since we began to predict ordinary storms with any scientific accuracy.

The first step toward long range predictions of the weather is a full understanding of the causes of present variability. It is agreed on all sides that theoretically the most hopeful line of study is solar variations. Yet as Mr. Birkinbine has shown, the attempts to establish a correlation between terrestrial climate and changes in the sun have hitherto proved disappointing. Even this, however, as is well said by Professor Bigelow, is no ground for discouragement. It simply means that we are dealing with a big problem which is highly complex. In spite of seeming contradictions no phenomena have yet been discovered which are not in harmony with certain forms of the solar hypothesis. What follows is an outline of an hypothesis which has not yet been before scientists long enough to be tested. Even if it is wrong in certain respects, it shows that there are abundant possibilities which students have not yet considered.

Hitherto the chief obstacle to a solar hypothesis of climatic variations has been the unfounded idea that all parts of the earth ought to respond directly and in the same fashion to changes in the sun. That is, it has been assumed that if the sun grows warmer or cooler the whole of the earth's surface ought also to grow warmer or cooler. As a matter of fact it is now established beyond dispute that when the sun gives out an unusual amount of heat, the earth's *surface* is unusually cool, especially in equatorial latitudes. The word *surface* is emphasized because it is possible, and indeed probable, that when the surface is unusually cool certain higher layers may be unusually warm. Another fact is almost equally well established, namely that when solar radiation is active, cyclonic storms such as tropical hurricanes and the more gentle but widespread storms of our own latitudes are also unusually active. These two facts are closely connected, and the second seems to explain the first.

This brings us to our hypothesis. The sun appears to exert an influence upon terrestrial temperature in two ways; the first is direct, when the sun sends out more heat, the earth is warmed; the second is indirect, when the sun is more active the atmospheric circulation is altered and thus the distribution of temperature is changed. The indirect influence apparently may neutralize or even reverse the direct. The mechanism by which this result seems to be produced is as follows: one of the most characteristic features of all storms,

whether they be tornadoes, thunder storms, hurricanes, or the ordinary storms of temperate latitudes, is that in the center there is an upward movement of the air. The air may move rapidly or slowly, but in either case the lower air is carried aloft to a considerable distance. Almost invariably the air which moves upward is either absolutely warm or at least warm for the given season and latitude. Every one knows that the air grows warm before a storm in winter and that thunderstorms in summer are apt to occur when the air is especially hot. The rising of the warm air is accompanied by a movement of cold air so that the general surface temperature is lowered. At times of many sunspots the number and intensity of storms and the rapidity of the general atmospheric circulation increase. The result is that more warm air is carried upward. Thus the earth's *surface* is cooled, although the upper air may possibly be warmer than usual. This seems to account for the apparent contradiction between greater solar radiation and lower temperatures on the earth.

Another supposed obstacle to a solar hypothesis of climatic variations has been the well known fact that in the same latitude and in places only a few hundred miles apart variations of a contradictory nature are frequently observed. When these variations are plotted upon maps, however, it is found that they follow definite laws and are directly related to the solar cycles. For instance, at times of many sunspots the total storminess of the North American continent increases, but the central part of the United States experiences a pronounced decrease. This occurs regularly in each sunspot cycle. The increase of storminess takes place primarily in a pronounced belt extending through southern Canada and only covering a small part of the United States. Another belt of increased storminess passes through our southwestern states and across the Gulf of Mexico, where it is very faint, to the Atlantic Ocean where it strengthens and turns northeastward.

The exact boundaries of the areas of increased and decreased storminess at times of many sunspots vary from cycle to cycle, although the general location and shape of the areas remain nearly the same. For example, at times of solar activity a tongue of increased storminess projects southward from Canada into the United States. In general the tongue lies over Lake Michigan, but its position shifts from cycle to cycle. When the recorded level of Lake Michigan is plotted for fifty years or more we find that

nearly two-thirds of the time the level of the lake rises or falls in harmony with the number of spots, but at other times the two disagree. Formerly such a phenomenon was thought to militate against the solar hypothesis. Now we see that it is what would be expected. When the tongue lies over Lake Michigan, we find agreement, but when it shifts away there is disagreement. Our task is to find why and when it shifts away. The explanation probably lies in the fact that there are many kinds of solar variations, which produce diverse effects and which occur with different periodicities. For instance, prominences, faculae and magnetic variations as well as the visible changes in sunspots all seem to represent variations in the amount of solar energy sent to the earth. Each of these apparently influences the atmospheric circulation, and hence causes variations in the weather. Moreover a single type of solar activity may have several kinds of periodicity. Sunspots vary in cycles of about 3, 8, and 34 years as well as the well known 11 year cycle. None of the cycles, however, is permanent or regular. The 11 year cycle varies from 7 to 15 years in length, and suffers corresponding changes in intensity. Thus the climate of the earth appears to depend upon a complex series of solar changes which may combine to help or to hinder one another. To these must be added certain purely terrestrial phenomena, such as the presence of volcanic dust in the atmosphere, which also play a part in determining the temperature and movements of the atmosphere.

It is impossible here to explain the solar hypothesis more fully. It is done at length in a paper entitled "The Solar Hypothesis of Climatic Changes" in the *Bulletin of the Geological Society of America*, volume 25, 1914. The point to be emphasized here is that in spite of many and authoritative statements to the contrary, a growing body of climatologists are convinced that the variability of the earth's climate from year to year and from decade to decade is primarily due to variations in one or another of the several kinds of solar activity. If so, there is good ground for hope that we may discover how the changes take place and how to predict them. When that occurs the importance of the contribution of waterworks engineers to civilization will increase greatly. They will be responsible not merely for the construction and maintenance of all sorts of projects, but for interpreting the predictions into deeds, and thus actively forestalling the enormous damage which rises from variations in precipitation.

Mr. Carl P. Birkinbine: Dr. Huntington's discussion is especially welcomed because his exhaustive investigations into past climatic changes permit him to add a record of one instance of a world wide interval of extreme precipitation and other climatic conditions, as well as mention several severe droughts in European countries. Some of these extremes mentioned have not been duplicated within the memory of any living person, probably the nearest approach being the unusually cold summer of 1816 along the north Atlantic coast, and also in some foreign countries. The full extent of this in the United States is not available because of the lack of records due to scanty population west of the Alleghenies, but not only in written records but also by word of mouth it has come down to us as "the year without a summer." Records of the general region in which Philadelphia is situated note that the winter months of this year were mild, and that the extreme unseasonable cold occurred in what we know as the hot months. The same region had, in 1915, a cool summer and therefore one marked by abnormal rainfall.

Dr. Huntington has noted an interval on the European continent when storms of unusual severity alternated with intense droughts, and some of the summers were so wet that reduction in crops, which we generally associate with deficiency in moisture, was produced by too much rain.

Included in the great disturbances of the fourteenth century was the violent tempest of January 15, 1362, which occurred in the midst of the great pestilence of London, the second pestilence. William Langland in *Vision of Piers Plowman*, Passus V, lines 13–15, wrote of it:

> He preved that thise pestilences were for pure synne,
> And the southwest wynde on saterday at evene
> Was pertliche for pure pryde and for no poynt elles.

and Fabyan says:

> In this xxxvii[1] yere, upon the daye of Seynt Mauryce, or the Xv daye of Januarii, blewe so excedynge a wynde that the lyke thereof was not seen many years passed. This began about evynsong tyme in the South, etc.

He states that it lasted for five days.

This storm is noticed again in Hardyng's Chronicles, and Blomefield relates that it blew down the spire of Norwich Cathedral.

[1] Referring to the reign of the sovereign.

Our climatic changes are a series of small cycles occurring within larger cycles, and these in turn within cycles of still greater magnitude, all being irregular in amplitude and period. Consequently we may expect that great extremes, which are produced by the most powerful causes, would cover enormous areas on the globe, while the small cycles may be confined to definite regions and greatly modified by local storm conditions and natural topography. It does not seem improbable to anticipate scientific progress which will give advance warning of the great and most unusual climatic conditions; and as engineering work is restricted to specific localities, we must use factors of safety which will forestall such damage as we are able to anticipate.

The solar hypothesis is the most satisfactory suggestion yet made of the causes of climatic changes, and when the studies of physicists and meteorologists can be based upon well coördinated and accurate data, frequently taken at a number of points, what now appear as discrepancies will be explained, and this complex problem at least brought to the point where additional research can follow a path more clearly outlined.